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PRINCIPLES OF CLASSIFICATION AND CORRELATION OF THE PRE-CAMBRIAN ROCKS[1]

I

CHARLES RICHARD VAN HISE

A half-hour summary of the principles of classification and correlation of the pre-Cambrian rocks can give no more than the barest outline of the subject.

In the classification and correlation of the pre-Cambrian formations we lack the guide of fossils. While life existed in pre-Cambrian times, and a few fossils are found in several areas, they are not sufficiently abundant to serve either for the purposes of classification or correlation. How far-reaching this handicap is will be realized when this paper is contrasted with those that follow. In considering the questions of classification and correlation of the later formations, fossils occupy a paramount position. It is true that the faunal breaks are often and probably are generally dependent upon physical causes, and the latter are frequently considered; but when the determinations are made, the fauna rather than the physical factors are given first place.

In the classification and correlation of the pre-Cambrian our sole criteria are physical. Therefore we have for the discriminations only those guides which for the fossiliferous rocks are commonly regarded as subordinate. It follows that with the pre-Cambrian rocks we are on less certain ground than with the later formations. However,

[1] Read before Section E of the American Association for the Advancement of Science, December, 1908.

the very fact that fossils are not available in studying the pre-Cambrian has led the workers in this field to a careful consideration of the physical criteria and their relative value.

Among the physical factors which have been used in the classification and correlation of the pre-Cambrian, the following are the more important: (1) Lithological character; (2) Continuity of formations; (3) Likeness of formations; (4) Like sequence of formations; (5) Subaerial or subaqueous deposits; (6) Unconformities; (7) Relations to series of known age; (8) Relations with intrusive rocks; (9) Amount of deformation; (10) Degree of metamorphism.

1. *Lithological character.*—The first step in the study of rocks from a physical point of view is to determine the character of the formations, series, and groups—whether igneous or sedimentary; if igneous, whether plutonic or volcanic, acid or basic; if sedimentary, whether psephite, psammite, pelite, limestone. While according to definition a formation is essentially a lithological unit, usually this unit is more or less composite, consisting of many somewhat variable beds and often of several members of different character. Because of the variability of the elements constituting a formation, there are an indefinite number of permutations and combinations of these factors. This results in giving a given formation, series, or group special peculiarities which often enable one to recognize it even when actual connections of the various outcrops have not been observed.

Accepting any of the current theories as to the history of the earth, the rocks of the earliest time are dominantly of igneous origin, and those of later time dominantly sedimentary. Since the earliest Cambrian rocks contain remains of all the great types of life, it is certain that antecedent to this time the more fundamental and greater part of organic evolution took place. Hence in a full pre-Cambrian succession we should expect the rocks of the early pre-Cambrian to be dominantly igneous and those of the later pre-Cambrian to be dominantly sedimentary. In accordance with the natural expectation, in practically all of the great regions of the world in which the pre-Cambrian have very extensive exposures, and in which close studies have been made, we find that the basal series of rocks is dominantly igneous, and the superior series dominantly sedimentary.

2. *Continuity of formations.*—Where formations in different districts are found to be continuous, they are supposed to be of the same age. It is realized that this conclusion is not absolute, for in the case of a great slanting transgression of the sea, the basal clastic deposits of the early part of the transgression may be considerably earlier than those in the later part, although the formations may be continuous. However, as yet given pre-Cambrian formations have not been traced to sufficiently great distances to introduce important errors upon this account.

3. *Likeness of formations.*—Where in different districts there are like formations, this is of assistance in correlation. Thus, if in several districts of a geological province but a single limestone formation is observed in any one, and the limestone of the different districts has the same peculiarities, there is a natural tendency to suppose all the limestone to be part of a single formation. However, the criterion of lithological likeness alone is not sufficient to establish identity. This is illustrated by the three iron-bearing formations of the Lake Superior region. Because these formations were of such an exceptional and peculiar character, and were so remarkably alike, it was supposed for a long time that they were of the same age. For a number of years this mistaken belief was a serious hindrance to an understanding of the succession and structure in this region. The weakness of lithological likeness in correlation is due to the fact that the same set of physical conditions has frequently occurred during geological time, and thus formations practically identical even in the combinations of their variations, including color, banding, nature of beds, etc., have been produced again and again.

4. *Like sequence of formations.*—Similar sets of formations in the same order furnish a criterion for correlation, of much greater consequence than the likeness of a single formation. But even this criterion has severe limitations, for similar sets of formations in the same order may have been deposited a number of times during a geological era; for instance, when a sea transgresses over a land area there are normally formed in order a psephite, a psammite, a pelite, and a non-clastic formation, and frequently over this, another pelite. Several such similar sets of formations are known in the pre-Cambrian in a single geological province.

5. *Subaerial or subaqueous deposits.*—Closely connected with the third and fourth criteria is the question as to whether the deposits were laid down under air or under water. It is clear that the conditions of deposition of these two classes of rocks are so different and the nature of the formations which may be contemporaneous so variable, that there is great difficulty in correlating the two. Also it is plain that the difficulties in correlating disconnected continental deposits are scarcely less great. Only recently has serious study been undertaken to discriminate subaerial and subaqueous deposits. This subject will not be gone into here, since it is one which has been recently discussed in several extended papers. I may, however, speak of one point. So far as we can yet determine the subaerial deposits are in general not so well assorted nor so likely to be sharply separated into distinct formations as the subaqueous deposits. This statement is believed to hold although it appears that under exceptionally favorable conditions the aerial deposits may be pure quartzose sands. Consequently cleanly assorted quartzose sands, pure limestones, and series composed of sharply contrasted formations are regarded as strongly favoring the idea of subaqueous deposition. As yet there is no evidence that air has the discriminating capacity which water has in producing cleanly assorted sands. If it is difficult to discriminate subaerial or subaqueous deposits, it is much more difficult to discriminate subaqueous deposits of the inland lakes and seas from those of the ocean.

6. *Unconformities.*—Unconformities are of great assistance in classification and correlation. It has been intimated that the great physical movements producing unconformities are frequently the real causes of faunal changes. Irving was the first fully to realize the importance of unconformities in correlation. The criteria by which unconformities are determined and their magnitude and significance analyzed cannot be discussed in a short paper. Those interested in this aspect of the subject must be referred to the original discussions.[1]

It should be remarked, however, that unconformities may have

[1] Roland Duer Irving, "On the Classification of the Early Cambrian and Pre-Cambrian Formations," *Seventh Annual Report*, U. S. G. S., pp. 365–454; Charles Richard Van Hise, "Principles of North American Pre-Cambrian Geology," *Sixteenth Annual Report*, U. S. G. S., pp. 724–34.

a very variable extent and significance. It is now realized that a sharp orogenic movement may take place resulting in uplift, erosion, subsidence, and therefore discordance of strata, which may not affect an adjacent area. Thus it should clearly be understood that it cannot be assumed that unconformities due to orogenic movements are more than of district extent. There are, however, great movements of uplift and subsidence which are continental and may be even intercontinental. Unconformities due to movements of this kind may have a very wide extent, and may thus be used for correlation from province to province, or possibly even from continent to continent. But in order that this may be fully done, it is necessary to show that the unconformity upon which correlation is based is an extensive one.

As yet insufficient careful study has been made of known unconformities from this point of view. Here is a great and fundamental field for investigation. If the known unconformities of the world were broadly studied, it is probable that many can be determined to be local, others to be provincial, others continental, and a few intercontinental. No more important determination than this remains to be made in geology. So far as I can see until this work is done there will be no very close correlation of pre-Cambrian formations from province to province and from continent to continent.

7. *Relations to series of known age.*—The relations of a formation, series, or group, to other formations, series, and groups of known age are of very great assistance in correlation. Frequently a formation, series, or group may be continuous or recognizable in the different districts of a geological province when other formations, series, or groups are not continuous. The position of the latter with relation to the former, whether above or below, and if above or below, conformable or unconformable, are valuable helps in correlation. Thus the Keweenawan is practically continuous about the entire Lake Superior basin. This is the only series of which this is true. The position of the series called Upper Huronian immediately but unconformably below the Keweenawan in different districts in connection with other facts is of great significance.

8. *Relations with intrusive rocks.*—The older is a series the more intricately is it likely to be cut by intrusive rocks, and this relation is of assistance in correlation in connection with other criteria. If a

series is intricately cut by igneous rocks, all of which stop at a definite horizon, this is strong evidence that the adjacent rocks free from such intrusives are later and probably belong to a different series.

9. *Amount of deformation.*—The amount and nature of the deformation are of assistance in correlation within limited areas. Upon the whole, the older a series the greater and more intricate the deformation. The difference in the amount of deformation in the pre-Cambrian series wherever there is a somewhat full succession of formations is sufficiently great to make this an important factor in the classification and correlation of the formation.

10. *Degree of metamorphism.*—The amount of metamorphism is a factor in correlation. Upon the whole, the older a series the more likely it is to be metamorphosed, but this criterion has severe limitations, since within comparatively short distances the closeness of folding and the quantity of intrusives may greatly vary, and these are very important factors in metamorphism. The worker among the pre-Cambrian rocks must have a very thorough understanding of the principles of metamorphism and the nature of the transformations through which rocks go. For, in working out the stratigraphy of the pre-Cambrian, if the criterion of the original character is to be used, it is necessary to know the rocks which the now greatly metamorphosed varieties represent.

GENERAL STATEMENT

In actually working out the succession of formations, series, and groups in the different districts of a geological province and in correlating them, all of the above criteria must be used. It is in judgment in appreciating the value of each of these criteria and their combinations that the skill of the pre-Cambrian stratigraphical geologist appears.

To this time, from my point of view, the only divisions of the pre-Cambrian which have been proved to be general, if not world-wide, are those of the Archean and the Algonkian. This subject I shall not take up in detail, since I have recently discussed it in another address.[1]

[1] Charles Richard Van Hise, "The Problems of the Pre-Cambrian," *Bulletin, Geological Society of America*, Vol. XIX, pp. 1–28.

However, it may be said in summary that the Archean is a group dominantly composed of igneous rocks largely volcanic and for extensive areas submarine. Sediments are subordinate. The Algonkian is a series of rocks which is mainly sedimentary. Volcanic rocks are subordinate. The Algonkian sediments where not too greatly metamorphosed are similar in all essential respects to those which occur in the Paleozoic and later periods. When the Algonkian rocks were laid down essentially the present conditions prevailed on the earth. The Archean rocks on the other hand indicate that during this era the dominant agencies were igneous. The physical conditions had not yet become such as to lead widely to the orderly succession of sedimentary rocks like those being formed today. On the whole the deformation and metamorphism of the Archean are much farther advanced than the Algonkian. The two groups are commonly separated by an unconformity which at many localities is of a kind indicating that the physical break is of the first order of importance. As evidence of this, at many places are the fundamental difference in the character of the rocks, the greater intricacy of intrusion, greater deformation and metamorphism of the older group, and deep intervening erosion. In some localities a part of these phenomena are lacking, but the significance of an unconformity is determined by the places where evidences of its magnitude occur rather than where lacking. So profound are the contrasts between the Archean and the Algonkian in each of the great regions of the world in which the pre-Cambrian has been studied, and so similar are each of these great groups with reference to the fundamental principles discussed that it has been regarded as safe to correlate these two groups even when in distant geological provinces. In making this correlation it is not supposed that the formations of one province are of exactly the same age as those of another province, but that the formations assigned to the Archean and Algonkian respectively in any given case belong to the two great eras of the pre-Cambrian represented by the rocks of these groups.

For extensive areas the Archean may be divided into Laurentian and Keewatin. These divisions are purely lithological, the former being mainly plutonic acid igneous rocks and the latter basic igneous rocks, largely volcanic. The Algonkian in many of the various

geological provinces may be divided into two or more series separated by unconformities. The formations of these series are commonly sedimentary, although igneous rocks are often abundant. As a whole, to the Archean group ordinary stratigraphical methods do not apply. To the Algonkian such methods are as applicable as to the Paleozoic and later series.

While the subdivisions of the Archean and of the Algonkian can be frequently equated in the same geological province, as, for instance, in the case of the Upper Huronian in the different districts of the Lake Superior region, it has not been found practicable to equate them from province to province. That is to say, one cannot be certain as to the correspondence of individual Algonkian series of China, Scandinavia, and of the Cordilleran region. If, as above suggested, it becomes possible to work out the physical history of the continents so that it may be determined which of the unconformities are continental, and intercontinental, or if in the pre-Cambrian rocks distinctive faunas are found, then closer correlation of the pre-Cambrian in different geological provinces may be possible than the Archean and Algonkian. In the meantime we must be content with the classification of the pre-Cambrian rocks in different geological provinces into Archean and Algonkian, with the understanding that the formations placed in each of these groups belong in a general way to the two early eras of the earth, during the first of which the agencies were dominantly igneous, and during the second of which the conditions had become similar to those of today. Further, within each geological province the Archean and Algonkian may be divided into series and formations which for each province are given local names.

THE BASIS OF PRE-CAMBRIAN CORRELATION.[1]

II

FRANK D. ADAMS
McGill University, Montreal

That was indeed a fair and sunlit earth which our predecessors, the first geologists, had presented to them for study. The uniform strata of the newer periods of our earth's history in their succession, well exposed, and following one another in due and regular order, everywhere contained abundant fossil remains which afforded a certain clue by which correlation could be made even in widely separated areas. We, their unfortunate successors, in pursuing our studies are obliged to descend into the deeper parts of the earth where the light begins to fail and when once we pass through that last grim portal into the drear pre-Cambrian world, we enter into what these earlier geologists regarded as a hopeless chaos. Here we lose the guiding thread of life, and the darkness deepens. At first we could dimly descry but the outlines of the vast indeterminate ruins of former worlds, but as our eyes become accustomed to the darkness these become somewhat more distinct and we recognize succession even in this ruined waste.

It may be that being a petrographer I overestimate the value of paleontology, but, like other things, we prize it most highly when it is lost and we are obliged to look for something to take its place. The working-out of the stratigraphical succession by detailed mapping in special areas teaches us much, but unfortunately the areas showing such succession are usually limited and isolated and the criteria for correlating the successions in separated areas, and especially in widely separated areas, are as yet undiscovered.

The vice-president of our section, Dr. Bailey Willis, in inviting me to take part in this symposium, has suggested that I should treat this subject of pre-Cambrian correlation if possible on broad lines, and I therefore venture today to follow Faust's aspiration, "Schau' alle Wirkenskraft und Samen," and present a certain aspect of the

[1] Read before Section E of the American Association for the Advancement of Science, December, 1908.

subject which I hope may at least be suggestive of a line along which some advance may be made in the correlation of these ancient rocks.

In his *Research in China* (Vol. II, chap. viii) Dr. Bailey Willis has put forward a theory to account for the origin of continental structure. In each of our present continents there are areas which during the evolution of the continent have always tended to rise—these he calls *positive* elements. There are certain other areas which have always shown a tendency to sink, relatively to the adjacent masses—these he calls *negative* elements. The movement of these elements is due to the greater relative density of the negative elements causing them to sink, while the relatively lighter positive elements tend to rise so as to bring about an isostatic adjustment. There have been horizontal movements as well as those in a vertical direction. These are of notable magnitude and their effects are seen in the schistose structure of these once deep-seated rocks and the overthrust and folded structures of the more superficial strata. The tendency toward vertical displacement has actually resulted in movement only at long intervals and during relatively short periods. Hence we may recognize cycles of diastrophism each one of which comprises (a) a comparatively brief period of orogenic and epeirogenic activity which results in elevated lands and restricted mediterranea; and (b) a comparatively long period of continental stability, which results in extensive peneplanation. The critical times which bring out continental structure are the epochs of diastrophic activity. During periods of inactivity the distinction between the positive and negative elements becomes less obvious and may even become obscured by extended peneplanation and marine transgression.

In a subsequent paper,[1] the same writer outlines the positive and negative elements of the continent of North America. The Canadian Shield, which is also called *Laurentia*, is at once the largest and the most readily distinguished positive element of the continent. It has an area of approximately two million square miles and the true boundary may be traced along the St. Lawrence Valley into the deep of Baffin's Bay and then north of the Arctic Archipelago (which is scarcely to be separated from Greenland) across the Arctic Ocean

[1] Bailey Willis, "A Theory of Continental Structure Applied to North America," *Bull. Geol. Soc. of America*, Vol. XVIII, p. 392.

and back to the mouth of the Mackenzie. Beneath the Cretaceous of western Canada, the margin of this element lies hidden. It ranges past Lake Winnipeg toward the state of Wisconsin, and then follows the shore of the Paleozoic mediterranean east to the Adirondacks and St. Lawrence.

Now it would seem, if we select a single positive element such as Laurentia—remembering that the critical diastrophic periods will be short and the intervening periods of deposition and accumulation will be of long duration—that these epochs of diastrophism, with their development of schistose structure in the moving masses and the associated phenomena of igneous intrusion, might be employed as a basis for the subdivision of Proterozoic time, and if the element moved as a whole, might even serve as a basis of correlation over the whole vast area. Laurentia, however, has not as yet been studied geologically except in a general way. Its detailed study will supply problems for generations of geologists yet unborn. Its southern margin alone, and that only in a few comparatively small areas, has been mapped in detail, but nevertheless exploratory and reconnaissance work has been carried out over almost the whole of the great expanse of this ancient continent chiefly by the officers of the Geological Survey of Canada, so that we have a good general knowledge of the main outlines, at least, of its geological history. It is proposed here to present a general statement of the results obtained, as they bear upon the history of Laurentia in pre-Cambrian times and afford a basis for pre-Cambrian correlation, making use of this principle of critical diastrophic epochs and drawing evidence from the area as a whole, rather than from a few restricted areas on its southern border.

This task is rendered comparatively easy owing to the fact that a critical digest of the mass of information concerning the pre-Cambrian rocks of the great central and northern portions of Laurentia, which is found disseminated through the reports and papers by the various geologists who have worked in this great area, has recently been prepared by Dr. George A. Young, of the Geological Survey of Canada, who has himself traveled very extensively in this northern country. I am indebted to Dr. Young for permission to make use of this unpublished material, but the original papers have been consulted in the case of all the more important occurrences.

The great expanse of Laurentia is underlain predominantly by the rocks of the Laurentian system. These consist of gneisses in infinite variety which in the majority of cases have the mineralogical composition of granite, although some present foliated varieties of rocks ranging from syenite to diorite. The foliation is in some cases so faint that it can be detected only on large weathered surfaces, but generally it is quite distinct or even striking. In addition to the foliation the rock often displays a very distinct banding due to the alternation of varieties of diverse character or composition. This foliation is in many, and possibly in the majority of cases, a primary structure and the darker bands very frequently represent included masses of overlying rocks, softened and in some instances partially digested. This foliation and banding was at one time regarded as a partially obliterated bedding and considered to present indisputable evidence that the rocks were of sedimentary origin. These gneissic rocks are not all of the same age, for frequently one mass can be seen to cut another. In addition to these gneissic granites, syenites, and diorites, however, the Laurentian comprises other kinds of plutonic rocks of very diverse character. Thus, from Minnesota to the shores of Ungava Bay, intrusions of anorthosite are found. Several of these, for the most part distributed along the margin of the protaxis in the province of Quebec and in the Ungava peninsula, present areas of from a few miles to 10,000 square miles in extent, and represent some of the more recent pre-Cambrian plutonics, although they themselves have been cut by still later granites. In fact, it is becoming more and more evident with the progress of geological investigation that the Laurentian is a vast complex of plutonic rocks of widely varying types and differing greatly in age, although there is no evidence to show that any of them were intruded later than the close of the Proterozoic. Whether in this enormously extended complex, which we term the Laurentian in the northern protaxis, there still survive any primitive sediments or any portion of an original crust, through which these great bodies of intrusive rocks forced themselves, is unknown. None have as yet been distinguished with certainty, but if any do exist they are probably similar in composition to these earliest intrusive rocks and might easily escape notice.

It is certain, however, that the overlying Keewatin and Grenville

series were deposited on some floor, although this floor has remained undiscovered up to the present time. Either the Laurentian gneiss, or some part of it, represents the original floor, subsequently melted and intruded into the overlying sediments, or the original floor remains unrecognized among the enormous bodies of intrusive rocks which resemble it in character.

Resting on this Laurentian complex, in the region of the Great Lakes, although penetrated by it, the lowest sedimentary series here recognized is the Keewatin series, a great body of rocks largely of pyroclastic origin, but in some districts containing great thicknesses of epiclastic material.

It is not necessary here to make further reference to this great series which has been so well described by so many writers. In this region it is the oldest sedimentary rock recognizable as such.

In the region of the St. Lawrence Valley this Keewatin is not seen, but there is a series of extraordinary thickness and enormous areal extent composed essentially of limestones, which rocks are practically absent in the Keewatin. Whether this series, known as the Grenville series, is the equivalent of the Keewatin is unknown as yet. If it be, the designation of the Keewatin by Van Hise as a series composed essentially of pyroclastic material to which stratigraphic methods cannot be applied and the assumption that such material characterized the earliest stratified deposits of the earth's history, must be abandoned, for the Grenville series is distinctly stratified and is one of the greatest limestones series in the earth's crust. However that may be, these two series constitute the oldest sediments in the earth's crust recognizable as such in their respective districts. Similar rocks apparently characterize extensive areas in the more northern and remote portions of Laurentia representing the oldest recognizable sediments in these districts.

At the close of this first period of long-continued sedimentation there came an epoch of diastrophism—a thrust exerted from a southeasterly direction against the ancient continent threw these series into a succession of great folds running approximately parallel to the present valley of the St. Lawrence. Enormous bodies of granitic magma rose in great bathyliths along the axes of the folds, disintegrating, fraying out, metamorphosing and partially absorbing the

lower surfaces of the invaded sediments. Everywhere over thousands of square miles these ancient sedimentary rocks can be seen to have floated on the granite magma or to have been sunk into it and to have been cut to pieces by apophyses of it. That these movements were, in many cases at least, very slow, is shown by the fact that a study of the primary gneissic structure displayed by the bathyliths demonstrates that the upward movement of the latter began before crystallization had set in and continued while the magma was slowly filling with the products of crystallization and until it finally froze into a solid rock. This epoch of diastrophism, resulting in the elevation of great tracts of country, brings to a close the first clearly recognizable chapter in the history of Laurentia.

After prolonged and profound denudation the sea again transgressed upon the continent of Laurentia and in this sea were laid down the strata of the earlier Huronian time. The sea at this time passed over what is now the region of the Great Lakes and extended at least as far north as Lake Mistassini and as far west of the head of Lake Winnipeg. Locally it evidently extended as far inland as the latitude of the northern end of Hudson Bay. Within this earlier Huronian time there was, following the deposition of the Lower Huronian, a period of subordinate elevation and depression in the district of the Great Lakes marked by the deposition of the Middle Huronian. At the close of this period of deposition, there was again an epoch of widely extended diastrophism due to a thrust exerted upon the southern portion of the continent from the ocean bed to the southeast and resulting in the widespread folding of the sediments which had been deposited over the southern portion of the protaxis, into a series of mountain ranges running in a northeasterly to southwesterly direction, with accompanying metamorphism of the folded strata and deep-seated intrusion of vast amounts of igneous rock. It may be that the great body of sediments forming the Grenville series really belongs to this rather than to the earlier Keewatin period, but be that as it may, these great orogenic movements which took place at the close of the earlier (Lower and Middle) Huronian time, brought to a close the second great chapter in the pre-Cambrian history of Laurentia.

There then followed a period of deep and long-continued erosion, during which the Lower and Middle Huronian and the underlying

sedimentaries were swept away over the greater part of the region, leaving only the lower portion of the folds—the roots of the mountains—in the form of long narrow belts, separated by the granitic rocks marking the axes of the intervening anticlinal uplifts. This period of profound erosion constitutes what Lawson has termed the Eparchean Interval. Up to this time the movements which affected the continent of Laurentia were due, as has been stated, to thrusts coming from the southeast and caused by the negative element underlying the Paleozoic plain in this direction, at that time constituting the ocean bed, by its subsidence crowding against the positive element which formed the continent of Laurentia. This is seen, as has been stated, in the distribution of the older rocks of the first two chapters of the pre-Cambrian in the form of long narrow belts running in a general northeasterly and southwesterly direction and representing the downward sagging portions of the ancient folds.

Succeeding this long period of intense and widespread erosion, which followed upon the conclusion of Middle Huronian or pre-Animikie time, there was again a very widespread transgression of the sea upon the surface of the continent of Laurentia. In this was laid down a series of sediments which while occurring at localities sometimes separated from one another by hundreds of miles, yet preserve the same general features. These younger rocks form chains of islands fringing the east coast of Hudson Bay over a distance of about three hundred miles and have been described under the title of the Nastapoka series. This assemblage of beds dips toward Hudson Bay, generally at low angles, and lies in long parallel ridges with steep eastern faces. The strata comprise a group of arkoses and sandstones overlain by sandstones, argillites, cherty limestones and dolomites and calcareous shales with great intrusive sheets of diabase. The series has been found in places to have a thickness of at least three thousand feet and is further characterized by the occurrence at certain horizons of beds of banded jaspilite and iron ores. In the interior of Labrador, where the series dips at low angles toward the Atlantic, there is throughout a zone at least three hundred miles long, a development of similar rocks and here again occur the jaspilite beds. On the Atlantic side, at the head of Hamilton inlet, and further up the river of the same name, occurs a similar series,

while on the Atlantic shores, far north, is found a great group presenting many like features. West of James Bay and south of Hudson Bay, rocks lithologically like the Nastapoka series underlie a hilly district rising like an island above the surrounding flat-lying Paleozoic beds. In this great district of the pre-Cambrian west of Hudson Bay, large areas bordering the Arctic about the mouth of the Coppermine River, and extending to Great Bear Lake, are underlain by a development of rocks resembling in nearly all respects the Nastapoka series and similar rocks have been described from the region about Great Slave Lake.

In all these widely separated localities great developments of the same rocks occur and often are accompanied by beds of jaspilite and iron ore. Everywhere the members present the same general arrangement, the strata cut by many faults, dipping at comparatively low angles and forming ridges frequently capped by diabase, while in most cases the beds have been found overlying with a most striking unconformity older granitic and gneissic rocks. These points of similarity seem to indicate that the scattered groups are all of about the same age and belong to a pre-Cambrian series probably at one time nearly continuous over the northern regions from the shores of the north Atlantic to about the valley of the Mackenzie. In Labrador and in the districts west of Hudson Bay the evidence indicates that the Nastapoka series was deposited after an epoch of severe erosion. Lake Mistassini, in northern Quebec, lies in a basin-like depression occupied by nearly flat-lying beds of cherty dolomite representing a portion of the Nastapoka series, while south of the lake these rocks have been found almost in contact with a development of the Lower (or Middle) Huronian, differing in no essential features from this group of rocks as found in numerous localities further southwest toward Lake Superior. The Lower Huronian is in a highly disturbed condition and has been penetrated by large bodies of granite. Neither the disturbances nor the granitic intrusions have affected the near-lying Nastapoka series so that the latter seems to be undoubtedly of post-Lower (or Middle) Huronian age, to have been formed after the Lower Huronian had been folded and invaded by the granites and then deeply eroded. The relation of the two series resembles that existing between the Animikie and Lower Huro-

nian at Port Arthur, and largely on these grounds the Animikie or Upper Huronian of the Lake Superior region and the Nastapoka series of Labrador and the territories south and west of Hudson Bay been have considered to be equivalent to one another.

The Nastapoka-Animikie series, forming the third major division of the pre-Cambrian in Laurentia, is of great importance, marking as it does one of the most widespread periods of submergence and depression in pre-Cambrian times, involving almost the whole continent of Laurentia. No division of the pre-Cambrian in Laurentia is exposed over such a great area of country. The positive movement which raised these rocks out of the sea was chiefly epeirogenic in character, for over the greater part of this area they still lie nearly flat. That the close of this time was, like those which preceded it, marked by an epoch of diastrophism, is shown by the widespread development of faults, accompanied in places by overthrusting. These are the superficial expression of the movements of deepseated intrusions, representing the last period of pre-Cambrian orogenic action. These post-Animikie granitic intrusions are to be seen on the east coast of Hudson Bay where, while the Nastapoka series in most places lies unconformably on the ancient Laurentian and the associated gneisses and schists, yet at some points it is cut by granitic intrusions.

This epoch of mild diastrophism brought to a close the third great period in the pre-Cambrian history of Laurentia.

The Nastapoka series seems to be the youngest division of the pre-Cambrian now found in the region east of Hudson Bay, but west of this inland sea, in a district bordering the southern shores of Lake Athabasca and stretching over an area of perhaps 24,000 square miles, is a great development of coarse sandstone in thick beds which along the shores of the lake aggregate at least four hundred feet in thickness. These, the Athabasca sandstones, lie in nearly horizontal positions, at times with a conglomerate layer at their base composed of fragments of the Laurentian granites and gneisses on which they rest with a strong unconformity. The Athabasca sandstones, or a very similar series, are exposed for a long distance up the valley which is continued seaward by Chesterfield Inlet, situated far north on the western shores of Hudson Bay. Between Lake Athabasca and the above locality, and in places associated with similar sandstones, are extensive areas

underlain by basic and acid volcanics, porphyrites, and porphyries. These sandstones and volcanic rocks are, by the Canadian survey, classed provisionally as of pre-Cambrian age and it seems not improbable that they are later than the groups of rocks about Great Bear and Great Slave Lakes which have been correlated with the Nastapoka series. Thus it is possible that the Athabasca sandstones and associated volcanics are the northern representatives of the Keweenawan of Lake Superior, concerning whose pre-Cambrian age there is a similar doubt.

These sandstones are composed chiefly of quartz grains which it has been supposed have been largely derived from a series of quartzites known as the Marble Island quartzites and which on the western shores of Hudson Bay occur at intervals over a stretch of about one hundred and twenty miles. These are associated with masses of dark schists, etc., lying in a disturbed condition. The presence of siliceous material in the widespread Athabasca series, so like that composing the quartzites, would seem to indicate that these latter were at one time also widely developed. What their equivalents elsewhere are, if they have any, is not yet known. They apparently are older than both the Athabasca and the Nastapoka series and may belong to some division corresponding to the earlier Huronian.

The rocks of the Athabasca-Keweenawan series are unaltered and lie practically flat. They have not been affected by orogenic disturbances or deep-seated plutonic intrusions. The uplift which raised them from the waters of the ocean was epeirogenic in character. Since the close of the pre-Cambrian, the continent of Laurentia, while preserving its character as a positive element, has undergone many oscillations, but orogenic or mountain-making forces have never manifested themselves, and the successive epeirogenic uplifts have resulted in and to a certain extent been compensated by the deep and long-continued erosion to which the continent has been subjected throughout the greater part of post-Proterozoic time.

Using therefore the epochs of diastrophism, which mark the successive stages in the pre-Cambrian development of the continent, as a basis of correlation, provisionally grouping the Athabasca Sandstones with the Nastapoka series, it would appear that we have three

major periods in the pre-Cambrian history of Laurentia separated by two critical epochs of diastrophism, with possibly a fourth period represented by the Laurentian rocks at the base of the series. That is to say we have three major periods in the pre-Cambrian succession separated by epochs of diastrophism, which diastrophism at each epoch exhausted itself for the time. These are as follows:

Neo-Proterozoic	Keweenawan-Athabasca
	Upper Huronian or Animikie-Nastapoka
Meso-Proterozoic	Middle Huronian
	Lower Huronian
Eo-Proterozoic	Keewatin
	(Intrusive contact)
	Laurentian (embracing the original crust, if any remains)

The lines drawn between the several subdivisions indicate unconformities, the heavier lines indicating the major breaks referred to in the text.

If we attempt to make a comparative study of the earlier continental evolution of North America and that of Asia, we note at the outset that the Siberian nucleus is a portion of that northern Polar region which comprises also Russia, Greenland, and Laurentia, against which stress has been continuously exerted by the denser masses of the more southern latitudes. As has been emphasized by Suess, the Siberian nucleus has been undisturbed since a pre-Cambrian date, and the same is essentially true of Laurentia also. We find that in Asia there were in geological time great mediterranea which, after they had been made the basins for the accumulation of great thicknesses of sediment, were successively closed by great thrusts from the south which folded up the sediments into mountain ranges and then converted these into dry land. In Europe the Alpine region was a marine strait in Cretaceous time, which was subsequently converted in this way into a mountain range.

In the North American continent, of which Laurentia forms a part, there seems to have been a somewhat similar sequence in continental development. Thus the Appalachian Mountains and the Cordilleran range of British Columbia represent ancient marine valleys or straits whose sediments are now folded into series of mountain

ranges. The thrusts which closed up these mediterranea and developed mountain ranges from them, were exerted in a northeasterly direction against the southwestern part of the continent, and in a northwesterly direction against the southeastern border of the continent, so that the folds are parallel to the margin of the present continent of Laurentia. If we inquire whether similar long, narrow, belt-like mediterranea existed in Laurentia in pre-Cambrian times, the answer seems to be in the negative. The surface of the continent seems rather to have had upon it at intervals throughout geological time a succession of large, irregular-shaped bodies of water, somewhat resembling the present Hudson's Bay, in which, however, great thicknesses of sediment were accumulated.

The sediments deposited in these bodies of water in Keewatin, Grenville, and the Earlier Huronian times, were folded up into mountain ranges crossing the southern portion of the protaxis in a northeasterly and southwesterly direction, coinciding with the course of the Appalachian folding.

The intense diastrophism which brought to a close the Eo-Proterozoic and again the Meso-Proterozoic time was exerted apparently as far north as the middle of Labrador and the southern portion of Hudson's Bay.

In the later pre-Cambrian mediterranea the Nastapoka-Animikie series and the Athabasca-Keweenawan series were deposited. The almost entire absence of orogenic movement at the close of this time, combined with the great extent and comparatively unaltered character of the rocks, makes the break at the base of the Nastapoka-Animikie series probably the most pronounced in the whole pre-Cambrian succession in Laurentia. Thousands of square miles of practically flat-lying sediments overlie remnants of a highly folded and metamorphosed antecedent series.

We thus have two major breaks in the pre-Cambrian succession, each marked by an epoch of diastrophism which exhausted itself for the time.

An identical series of two major breaks in the Proterozoic succession, marked by epochs of pronounced diastrophism which in each case exhausted itself, is found in the Asiatic portion of the nucleus.

The succession here is as follows:[1]

Neo-Proterozoic..... (Hu-t'o system).....	Tung-yu limestone T'ou-t'sun slates	Slates, limestones and quartzite.
Meso-Proterozoic..... (Wu-t'ai system).....	Si-t'ai series	Chiefly chlorite schist; quartzite conglomerate at the base.
	Nan-t'ai series	Siliceous marble, jasper, quartzite, and schist.
	Shi-toui series	Mica schists, gneiss, magnetite quartize, and basal feldspathic quartzite.
Eo-Proterozoic.....	T'ai-shan complex	Basal complex of varied gneisses and younger intrusions.

The lowest of these series, the T'ai-shan, resembles the Keewatin penetrated by Laurentian intrusions, being

> a metamorphic complex, the constituents of which are largely igneous, though perhaps in part sedimentary in origin.[2]

This was brought to a close by a period of intense diastrophism. Succeding this:

> We distinguish with great certainty a great thickness of very early Proterozoic sediments—the Wu-t'ai—which were intensely deformed and metamorphosed during a mid-Proterozoic epoch of orogeny, owing to pressure exerted by the outlying negative elements, and a later Proterozoic series—the Hu-t'o—which represents shore conditions and which was moderately deformed by pressure exerted by the same cause at the close of the Proterozoic.

Applying therefore this criterion of diastrophic epochs to the correlation of the Proterozoic succession of these widely separated portions of the great northern nucleus, we obtain an identical result in both cases—the diastrophic movements seem to have affected the nucleus as a whole.

It would seem that these diastrophic epochs designate certain of the unconformities in the succession both in the Siberian portion of the nucleus and in Laurentia, as major, dominant, and of special importance, and others as subordinate and of minor importance. We thus have indicated a division of the Proterozoic into Eo-, Meso- and Neo-Proterozoic. On this basis of correlation the T'ai-shan corresponds to the Keewatin-Laurentian complex; the Mu-t'ai to the Lower and Middle Huronian, and the Hu-t'o to the Animikie-Nastapoka series.

[1] *Research in China*, Vol. II, p. 4. [2] *Ibid.*, Vol. I, Part I, p. 19.

These major breaks would seem to be as well marked and as important as those which characterize the separation of the Eo-Paleozoic and the Neo-Paleozoic in eastern America, or perhaps as that which brings to a close the Paleozoic succession in Europe.

If, as our knowledge of the pre-Cambrian becomes more complete, the correlation of these rocks over great areas by a time relation to diastrophic epochs proves to be generally applicable, we have a basis of correlation of great value and importance. This will constitute a great advance as compared with our present methods, which afford no adequate means of determining the relative values of unconformities and thus the successions in the most distant parts of the world are now being matched with each other and an unwarranted satisfaction is manifested if the number of unconformities in the pre-Cambrian succession in different continents is approximately identical, and a sure and certain hope that all will prove to be satisfactory is expressed if there is no agreement.

All that we really know at present is that

> there are great sequences of pre-Cambrian sedimentary formations, separated by many gaps from each other, which give one picture, growing less distinct in outline the farther back one goes, of the remotest periods of geological history, or, in other words, of periods of the earth's pre-historic age which is, according to the author's opinion, probably of greater length than all subsequent geological time.[1]

It is believed, however, that through the recognition of these diastrophic epochs, the dominant outlines of these pictures may perhaps be more clearly brought out and the relative values of the different parts thrown into relief in the case of each individual positive element, and that these epochs which have marked the successive stages of advance in Paleozoic and Mesozoic times, may thus be employed with advantage in deciphering the history of the pre-Cambrian as well.

DISCUSSION

CHARLES R. VAN HISE

It is with pleasure that I discuss briefly Dr. Adams' paper, since, allowing for differences of terminology, I find him in nearly complete accord with the

[1] J. J. Sederholm, *Explanatory Notes to Accompany a Geological Sketch Map of Fenno-Scandinavia*, Helsingfors, 1908, p. 31.

United States geologists in reference to the succession and relation of the pre-Cambrian series of Canada. So far as there are differences they will appear below.

The elucidation of the pre-Cambrian succession for the Lake Superior region, which term as here used includes the great tract extending from the Lake of the Woods to north of Lake Huron and south to the Paleozoic rocks, has been the work of many men extending through many years. In 1892, when *Bulletin 86* of the United States Geological Survey, on the Archean and Algonkian appeared, the Lake Superior succession, as now recognized, had been fully worked out,[1] with the exception that what was then called the Lower Huronian has since been found to comprise two series; also the series now called Keewatin was called Mareniscan, but was properly defined. Some years after the publication of this bulletin, Mr. A. E. Seaman discovered the unconformity mentioned in the lower Huronian of the Marquette district. As soon as this discovery was made it was appreciated that the two divisions of the Huronian in the original Huronian area worked out by Pumpelly, Leith, and myself, correspond with the two divisions in the Marquette district. The classification of the pre-Cambrian as thus developed was fully accepted by the International Geological Committee in 1904, and the table giving the succession was published by Leith in 1904, and by the committee in 1905, as follows:[2]

CAMBRIAN
Upper sandstones, etc., of Lake Superior
Unconformity
PRE-CAMBRIAN
Keweenawan (Nipigon)
Unconformity
Huronian: Upper (Animikie)
Unconformity
Huronian: Middle
Unconformity
Huronian: Lower
Unconformity
Keewatin
Eruptive contact
Laurentian

This succession is repeated by Dr. Adams in his communication, except that the unconformities are omitted, and it is extended to the entire Canadian pre-Cambrian region.

It is indeed gratifying to have completely accepted for the great Canadian pre-Cambrian area the succession which has been worked out for the Lake Superior region, but Dr. Adams implies that his classification rests upon a sounder basis than the same classification offered by others since "drawing evidence from the area as a whole rather than from a few restricted areas on its southern border." But unhappily for the contention of Dr. Adams, it is still true that the Lake Superior region is the only very extensive area in which the detailed geology has

[1] C. R. Van Hise, "Archean and Algonkian," *Bull. 86*, U. S. G. S., p. 195.

[2] *Journal of Geology*, Vol. XIII, p. 104.

been worked out and the full succession given in the table has yet been found. Also when the succession was originally worked out all available information in reference to Canada as a whole was considered and it was suggested that within the regions about Hudson Bay and the Copper Mines Rivers, the equivalents of at least two divisions of the Huronian and of the Keweenawan appeared to be present.[1]

As to the question of a floor for the Keewatin, according to our view, the Keewatin is simply the most ancient series which has been discovered to the present time. Naturally being the oldest series discovered, we have not yet found the rocks upon which it was laid down, and we make no assumption in this matter. Dr. Adams speaks of the Keewatin as a sedimentary series. If he means by this that it is a series laid down at the surface, this characterization is correct. However, we have frequently pointed out that this series is essentially composed of igneous rocks, including both lavas and fragmentals, and is only very subordinately of ordinary sediments.

As to the position of the Grenville series, I hold my opinion in reserve. Miller and Knight have shown that in the Hastings district where the series which Adams places in the Grenville is most extensively developed, there is an unconformity in the sediments. It is their belief that the greater part of the Hastings sediments, including the great limestone of Adams, belongs above this unconformity, below which is the Keewatin. If they are correct in this view, the larger part of the Hastings series included in Adams' Grenville belongs not with the Keewatin but with the Lower or Middle Huronian.

Dr. Adams says in reference to correlation by diastrophism: "This will constitute a great advance as compared with our present methods, which afford no adequate means of determining the relative values of unconformities, and thus the successions in the most distant parts of the world are now being matched with each other and an unwarranted satisfaction is manifested if the number of unconformities in the pre-Cambrian succession in different continents is approximately identical, and a sure and certain hope that all will prove to be satisfactory is expressed if there is no agreement."

In my address before the Geological Society of America a year ago, I introduced the table of pre-Cambrian series for China with their separated unconformities as given by Willis. I remarked that the Lake Superior Algonkian series in their number and their separating unconformities present a remarkable similarity to the Algonkian of China, but said it would "not be well to too strongly emphasize the close correlation suggested." Also I mentioned the "possibility that in the future we may be able to correlate the unconformable series of the Algonkian in provinces separated as far from one another as the Lake Superior region and Northern China."[2]

[1] Charles R. Van Hise, *Bull. 86*, U. S. G. S., pp. 496–502, 1892; *16th Annual Report*, U. S. G. S., Part I, pp. 807–9, 1896.

[2] "The Problem of the pre-Cambrian," *Bull. Geol. Soc. of Am.*, Vol. XIX, p. 26.

Dr. Adams in his paper repeats the quotation from Willis and makes an identical suggestion as to correlation, but implies that this is done upon the basis of diastrophism. Evidently he thinks that there is an "unwarranted satisfaction" in the first case and not in the second.

Each unconformity between any two series of the Canadian region or of China means that between their depositions there has been an epoch of diastrophism and one of erosion. I should be interested to know how the extents and the magnitudes of pre-Cambrian diastrophisms are to be determined except by studying the extents and magnitudes of the unconformities, that is, the extent and amount of the foldings, metamorphisms, erosions, etc., which intervened between the various series. In the paper which I have just read I pointed out that some unconformities are local, some regional, and some probably intercontinental. Adams points out that diastrophism may be regional or intercontinental. Is the distinction between the two greater than difference in language? One we may suggest talks English, the other Esperanto. Evidently if satisfaction is unwarranted in one case it is unwarranted in the other.

I am obliged to dissent altogether from the reasoning in Dr. Adams' paper which makes discriminations as to the magnitudes of the various breaks, upon the basis of Willis's hypothesis of positive and negative continental elements, and upon assumptions as to the sources of the thrusts. Even if these theories be assumed to be correct we do not know that they apply to the North American pre-Cambrian region, for we know nothing of the extent and distribution of the various pre-Cambrian series which are hidden under later rocks. In the western United States where extensive areas of pre-Cambrian protrude through the later rocks, and also in the Mississippi Valley, where are isolated areas of pre-Cambrian, several pre-Cambrian series occur, some of which are probably the equivalent of the series found in the Lake Superior region. Evidently the various pre-Cambrian diastrophic movements cannot be assumed to be limited to the surface areas of pre-Cambrian.

The question of the major groupings of the pre-Cambrian series I shall not attempt to go into in detail, since to do this would result in leaving less emphatic the reality of the accord as to the pre-Cambrian succession which has now come about and which I trust has come to stay between the Canadian and United States geologists, through the acceptance for Canada of the succession mainly worked out in a great area along the southern border of the pre-Cambrian region.

However, I may recall that I fully discussed the major classification of the pre-Cambrian in my presidential address before the Geological Society a year ago, and gave reasons for the primary divisions of the pre-Cambrian into the Archean and Algonkian. In that address I gave objections to a zoic classification, similar to but not identical with that which Dr. Adams adheres to. His proposed major classification is eo-proterozoic, meso-proterozoic, and neo-proterozoic. These terms imply that the pre-Cambrian had three distinctive life periods, an *eo*, a *meso*, and a *neo*. This may be the case, but until fossils are

found in the pre-Cambrian in sufficient abundance to justify a zoic classification, there can be no sufficient warrant for proposing that the major divisions of the pre-Cambrian be made upon a zoic basis.

CLOSING DISCUSSION BY THE AUTHOR

The aim of the paper on "The Basis of Pre-Cambrian Correlation" was, as stated, to suggest a method by which it might be found possible to correlate the various subdivisions of the pre-Cambrian rocks over widely extended areas rather than to enter upon a discussion of the classification of the pre-Cambrian of North America.

With regard to this latter classification, however, it must be pointed out that the paper shows that in a general way the classification adopted by the International Committees (United States and Canada) on the "Correlation of the Pre-Cambrian Rocks of the Lake Superior Region" and on the "Pre-Cambrian Rocks of the Adirondack Mountains, the Original Laurentian Area of Canada and Eastern Ontario," probably forms a satisfactory basis upon which the classification of the whole expanse of the great pre-Cambrian development of the Laurentian protaxis can be founded. Professor Van Hise is mistaken in stating that in the paper under discussion the succession recognized by these committees was adopted but that the unconformities were omitted, for in the wall diagram used to illustrate the paper, and upon which the succession of the pre-Cambrian rocks in Laurentia and China was set forth, the unconformities were especially indicated, black lines being used to show those which were of minor importance while broad red lines appropriately emphasized the major breaks in the succession. The unconformities and their relative importance are also shown in the text of the paper. In fact, this is the crucial point of the paper so far as Laurentia is concerned.

Professor Van Hise has insisted, in a long series of papers, that in the pre-Cambrian succession of North America there is one break which in importance far transcends all others, namely, that at the close of the Keewatin. Professor Lawson, however, has insisted that in this succession the chief break lies at quite a different horizon, namely, at the base of the Animikie.

The International Committees, while recognizing the succession of the various elements of the pre-Cambrian, absolutely declined to commit themselves to any opinion as to the relative magnitude or importance of the several unconformities which they recognized.

A study of all the work—much of it recent—which has been done in the more northern portion of Canada indicates that Professor Lawson's break—the Eparchaean Interval as he terms it—is one of the greatest unconformities in the whole pre-Cambrian succession of Laurentia, and probably quite as important, if not more so, than the break at the close of the Keewatin, and that the pre-Cambrian rocks are represented, not by two great systems entirely distinct and separated from one another, but by three great systems.

In Professor Van Hise's presidential address he has referred to the succession of the pre-Cambrian rocks in Scotland, Finland, and China as determined by Geikie, Sederholm, and Bailey Willis, respectively, and notwithstanding the fact that in these successions from one to six unconformities exist, he has in each case selected one unconformity as of paramount importance, and correlating this with the break at the summit of the Keewatin in North America, has held that these various successions support a dual division of the pre-Cambrian rocks which he has maintained to be world-wide. He closes his address as follows: "I wish to express my firm belief that the dual division of the pre-Cambrian into two great groups of rocks [Archaean and Algonkian] seems now as firmly established as the division between any other two groups." I feel, as stated in the paper, that in this conclusion an "unwarranted satisfaction" is expressed.

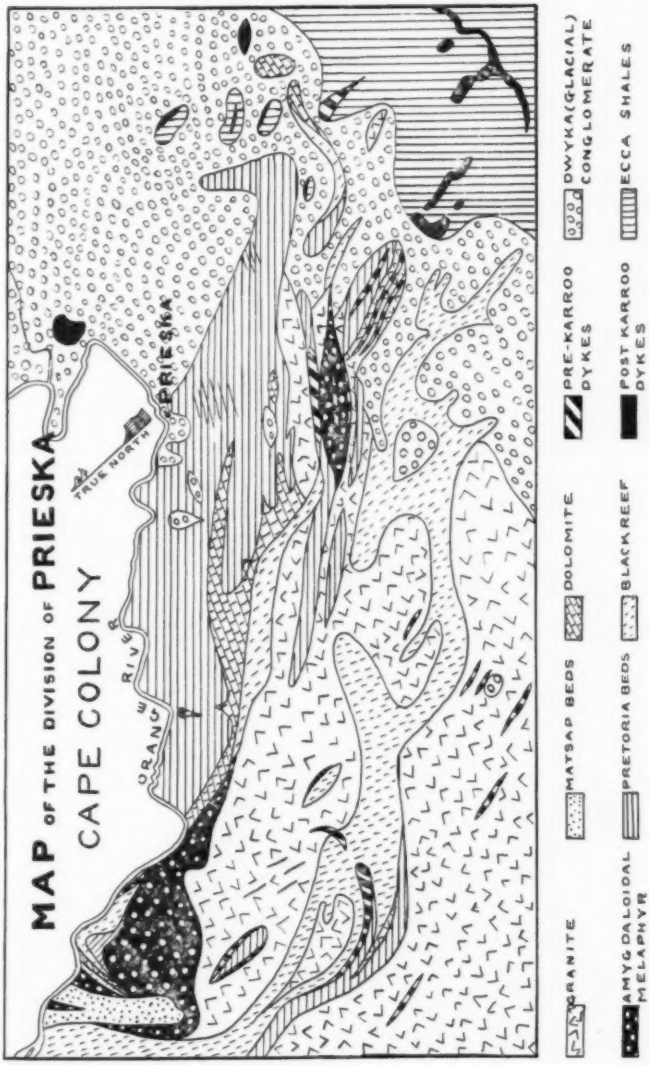
To sum up, therefore, it seems that the division of the pre-Cambrian rocks of Laurentia into two great major divisions—Archaean and Algonkian—is not supported by the facts in our possession. The pre-Cambrian succession is apparently rather threefold, which three divisions may, for convenience, best be designated as Lower, Middle, and Upper (Eo- Meso- Neo-) Proterozoic, quite independent of any consideration of the presence or absence of life.

THE PROBABILITY OF LARGE METEORITES HAVING FALLEN UPON THE EARTH

PROFESSOR E. H. L. SCHWARZ, A.R.C.S., F.G.S.
Rhodes University College, Grahamstown, Cape Colony

From time to time the accumulation of new facts in any one science renders it necessary to examine into the cause for the existence of certain features, and to see whether some small points which rendered the earlier explanations not altogether satisfactory, may not be entirely accounted for in the light of the new experience. In many cases this proceeding has resulted in the entire recasting of our ideas concerning certain phenomena, especially in the physical sciences where laboratory demonstration can prove the truth of the new law; in geology, the unwieldy nature of the subject-matter, and the different aspects which the same country or mountain may present to different observers, renders this method somewhat unsatisfactory. It must, however, be done, if the science is to progress, although in the end a categorical statement that the new explanation is a true one, and the old one a false one, cannot be made. It is the purpose of this paper to pick out certain facts in connection with the amygdaloidal lavas of Prieska, Cape Colony, which cannot readily be explained on any of the theories of igneous extrusion, and to see whether they cannot be accounted for on some other theory; I shall summarise what is known of the fall of large meteorites and point out in what way the phenomena connected with these show certain significant resemblances to those exhibited by the amygdaloids of Prieska, tentatively suggesting that in the past huge bolides fell on the earth, melted the rocks in the neighborhood of the fall and produced these great fields of lava.

The meteorites that we examine in the collections of museums are small and would not by their fall make much impression on the earth: it is true that in the course of ages these small meteorites must add considerably to the bulk of the earth for it is estimated that some hundred thousands, if not some millions, of meteoric bodies fall upon the earth each day. Even these museum-specimen meteor-


MAP OF THE DIVISION OF PRIESKA
CAPE COLONY
ORANGE RIVER
PRIESKA
TRUE NORTH
GRANITE
AMYGDALOIDAL MELAPHYR
MAYSAP BEDS
PRETORIA BEDS
DOLOMITE
BLACK REEF
PRE-KARROO DYKES
POST KARROO DYKES
DWYKA (GLACIAL) CONGLOMERATE
ECCA SHALES

ites, as I may call them, range up to sizes which would shake considerable areas of country by their fall, as for instance the Bacubirite meteorite, which is thirteen feet long and is estimated to weigh 50 tons.[1]

In the Coon Butte, Ariz., there is a crater which was described by Gilbert as volcanic, but subsequent investigation has failed to discover any volcanic material connected with it; on the other hand, strewn round it are masses of meteoric iron of which ten tons have been carried away at different times and now figure in collections as portions of the Canyon Diabolo meteorite. The rocks in the vicinity of Coon Mountain consist of horizontal beds of Aubrey limestone and sandstone belonging to the upper Carboniferous series. The mountain is formed by the up-turned edges of the strata making a jagged circular ridge varying in height from 120–30 feet above the plain. The chasm is 600 feet deep and 3,800 feet across. The nearest lava flows and cinder cones are twelve miles distant, while the San Francisco mountains which contain many volcanic cones are 45 miles away. The material at the bottom of the crater has been investigated by Messrs. Barringer and Tilgham by means of bore-holes down to 1,000 feet, and the rock encountered is mostly pure white silica which in some places is in the form of impalpable powder; scattered throughout this there are masses of varying sizes of pumiceous and more compact material, which chemical and microscopic examinations show to have been formed by the crushing and fusing of the quartz sandstone. Below the zone of crushed and fused material there is an underlying sandstone quite intact and unaltered.[2]

There seems to be no reasonable doubt that this crater is actually the result of the impact of a huge bolide and the absence of the large meteor itself is explained by supposing that the heat of the impact was sufficient to melt and perhaps vaporise its substance; certainly there is a large quantity of magnetic iron oxide lying as dust about the neighboring country, which, on analysis, gives a notable percentage of nickel.

[1] H. A. Ward, "The Bacubirite Meteorite," *Proc. Rochester Acad. Sci.*, 1902, IV, p. 67.

[2] D. M. Barringer, "Coon Mountain and Its Crater (Arizona)," *Philadelphia Acad. Nat. Sci. Proc.*, 1906, LVII, p. 861; B. C. Tilgham, *ibid.*, p. 887; G. P. Merrill, *Smithsonian Miscellaneous Collections* (quarterly issue), L, 1907, pp. 203, 461.

A large meteor need not necessarily be an iron one, and we have a remarkable block of melilite-basalt in Cape Colony which has certain features that point to its possible meteoric origin. The occurrence is at the top of the Spiegel River Valley in Riversdale; the outcrop of the rock is about 100 feet in an east-and-west direction, and half as much across, though, as it is found at the top of a hill, and the sides are strewn with débris from it, it is hard to determine the exact size of the block; there are bands of harder and softer material in it which give the mass the appearance of being bedded, and the dip is some 15° to the southeast. It is surrounded on all sides by coarse, loose conglomerates of Cretaceous age which show no disturbance whatever. Had the mass come up in a volcanic throat, one would have expected to see some evidence of the explosive force in the loose gravel, or some lateral dykes or fume vents, but nothing of the sort could be found, and no other volcanic rocks occur within many miles. The view adopted by the Geological Survey[1] is that it is a volcanic pipe filled in, but that is simply because no similar blocks have been described with which to compare it whereas melilite-basalt ordinarily occurs in connection with volcanoes.

If we turn to the moon whose surface being free from erosion and deposit should show clearly any marks made on it by the fall of meteorites, we find certain evidence which is highly suggestive. The craters which are scattered so freely over the moon's surface were thought by Gilbert[2] and others to be due to the impact of meteors; that they were not so formed we gather from the following considerations. In some of the craters the floor or top of the lava column stands many hundreds of feet below the general level of the surface, but in others the floor is as much above that level. The internal walls of the craters show definite terraces like old strand lines which have been formed by the successive retreat of molten material within the volcanic chimney. The craters, especially the smaller ones, often lie upon definite lines of fissures like the volcanic fissures of Iceland, an arrangement which would have been impossible had they been formed by the infalling of meteors. Lastly there is a regular

[1] A. W. Rogers and E. H. L. Schwarz, *Ann. Rept. Geol. Comm.*, 1898, Cape Town, 1900, p. 62.

[2] G. K. Gilbert, *Bull. Phil. Soc. Washington*, XII, p. 241.

scale of dimensions corresponding with antiquity in the craters, the larger being the older and the smaller ones successively younger; this we can establish both from the fact that the smaller ones often breach the larger ones, as well as from the freshness of the rocks about the smaller ones as compared with those surrounding the larger ones; for although there is no atmospheric weathering in the moon, the alternate heating and cooling of the surface brings about a certain amount of alteration which in time produces sufficient effect to be clearly noticed through the great telescopes.

These craters do not belong to volcanoes such as exist on the earth but resemble rather the outbursts of entangled molten matter during the final consolidation of the moon, according to Professor T. C. Chamberlin's view,[1] and on such a theory the graduation in size is well accounted for. But after this stage was over, when the forces which brought the molten material from the interior to the surface had become spent, no matter what their actual nature was, then the surface of the moon was deluged with floods of lava, which, over tracts many hundreds and thousands of square miles in area, obliterated all pre-existing features and in their margins invaded and ruined the craters which stood in the path of the molten liquid. These *Maria* or dark patches of the moon occupy roughly one-third of the visible portion, and as seen through the great telescopes which bring the moon's surface to within 40 miles of the observer, their margins show that the material of which they are composed flowed in upon the rough ground as very liquid lava would do. It fills in the lower ground forming numerous bays, and in many instances, as is the case of the crater Doppelmeyer, it distinctly appears to have melted down the side of the crater-wall next to it and to have filled in the cavity to its own level. This feature is not confined to any one spot of any one *mare*, but is to be noticed throughout the several thousand miles of the extent of the margins, and leads one to the conclusion that the *maria* were formed by a once fluid matter of the sea inundating firm land. The quantity of igneous matter was very great, and in each *mare* or sea it seems to have appeared all at once, there being no mark of successive flows such as compose the extensive lava fields of the earth. The lava of the several *maria* never overlap, although the

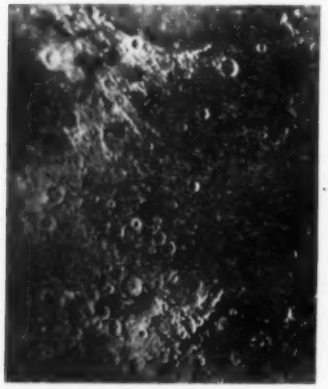
[1] T. C. Chamberlin and R. D. Salisbury, *Geology*, II, p. 105.

gravitative attraction on the moon being only one-sixth what it is on earth, would allow very steep slopes at the front of even fluid lava flows. The origin of this lava is still hypothetical, but it is to be noticed that none of the volcanoes of the moon give forth freely flowing streams of lava, nor do any of the numerous fissures or faults on the lunar surface, some of which evidently penetrate deeply, distinctly give rise to lava flows; generally it is established that all the volcano-like openings appear always to have retained their lavas within or near their walls, or, in other words, there was no tendency for lava to pass up to the surface in large quantities.

There is no evidence in any of the *maria* that the lava came up from a central pipe or from an elongate fissure; the general form of the seas is rounded or oval, and it would seem to indicate that if the fluid came from within, the lava should have emerged as from a terrestial volcano pipe, for if it came from fissures these should have been of elongate shape. But if the lava came either from fissured or from pipe-like openings there should be a grade to the flow extending from the center of the field to its margin; owing to the slight value of gravitation this grade should be steep. There, however, is no trace of such a slope; on the contrary, the curve of the margin of illumination shows the surfaces of the *maria* are essentially horizontal.

The hypothesis which fulfils most of the conditions of the case with respect to the origin of the lava of these *maria* in the moon is that great meteors fell upon the moon and by their impact produced sufficient heat not only to melt up their own substance but a good deal of that comprising the adjacent lunar surface. Even beyond the seat of impact, the shearing strains would probably be sufficient to convert much of the material of the surface into a fluid state, with the result that a mass of lava of a very high temperature, equal at least to the bulk of the invading body and probably several times as great, would be sent radially from the point where the impact took place. The evidence of melting effected by the material which forms the plains of the *maria* is considerable at several points, notably in the case of the craters on the margins of the seas. It seems quite certain that the walls of these craters next the sea have been in some manner effaced by contact with the material which came against it; in the case of the crater Flamstead in the Oceanus Procellarum, the

crater-wall has been almost melted down, but still rises slightly above the surface of the inundation; good examples are also seen in the Mare Tranquilitatis, Fig. 1. At many points the material forming the *mare* comes against extended steep-faced cliffs, which have the same general character as the inner slopes of the great craters, where the form of the declivity certainly has been determined by the melting action of the lava of the base. Further, where there are depressions in the area in the borders of the *maria*, the material of which they are composed flows into them as a fluid would have done.



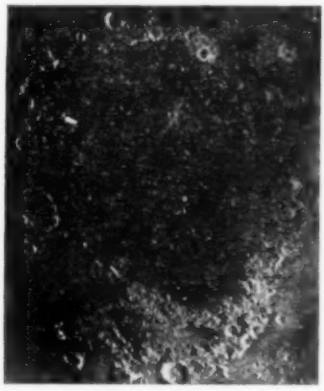


FIG. 1 FIG. 2

PHOTOGRAPHS OF THE MOON'S SURFACE, AFTER N. S. SHALER

FIG. 1.—Mare Tranquilitatis with Mare Serenitatis in the upper portion of the plate, showing the margin invaded by lava floods.

FIG. 2.—Mare Serenitatis, showing on the left the large crater Posidonius and above it the crater le Monnier which has part of its wall broken down by the lava of the *mare*.

The great objection to the hypothesis that the *maria* were formed by molten rock produced by the impact of large bodies falling upon the surface of the moon is that similar bodies competent to generate a great deal of heat have not fallen upon the earth's surface in the time which has elapsed since the beginning of the geological periods; there is so far indeed no recorded geological reason for supposing that they have ever fallen upon the planet, but it is just such evidence that I wish to submit. It must, however, be remembered that the moon's

surface took its shape long before the beginning of our geological record, so that if such evidence is to be found on the earth, such lavas of extra-terrestrial origin must be among Archaean rocks, where the unraveling of the tale would be extremely difficult, or they would be hidden under superincumbent strata. It is to be noted also that even in this stage of the evolution of our solar system there remain bodies in order of size such as would in falling upon the surface of the larger spheres produce the effect which we observe in the *maria;* thus the group of asteroids between Mars and Jupiter, though generally of far greater mass than would be required by impact to melt the larger of the *mare* fields, probably contains many bodies which in case of collision with our satellite would bring about the consequences which can be noted. At least one such mass of matter, Eros, has recently been discovered at no great distance from the earth.[1] It is probable that in a former state of the solar system when the moon was assuming its present surface features, these detached masses of matter were more abundant than they are at present. The tendency would be for those near the great spheres to be drawn in upon them, with the result that they would become rarer near the planets and the larger satellites.

Having then established the fact that giant meteors may have fallen on the earth and may have melted up tracts of country which would be deluged with lava without apparent vent or orifice from the interior, we can legitimately inquire whether there are any evidences of such occurrences on the earth's surface? There are many vast tracts of lava known on the Earth which offer tempting fields for speculation in this connection, such as the great lava sheets of the Snake River in Idaho, the Deccan traps of India and the Kapte Plains of British East Africa, and even the occurrence on these of small cinder cones and beds of ash and tuff does not necessarily prove that the material came from the interior of the earth, any more than the small blister cones on a flow of molten iron prove that the subjacent floor is riddled with blowholes, but I wish in this introductory statement to confine my remarks to one field which I know thoroughly.

In the district of Prieska, south of the Orange River, there is a

[1] N. S. Shaler, "A Comparison of the Features of the Earth and the Moon," *Smithsonian Contributions to Knowledge*, XXXIV, No. 1438, Washington, 1903.

tract of country which has been cleared of its covering of glacial drift and stands today with many of the features which it presented in a remote geological period. The glacial drift is of Permian age, and the topography revealed with astonishing freshness, belongs to that or earlier epochs. The area was described by Dr. Rogers and myself in 1899[1] and consists of a base of granite on which rest the various formations of the Transvaal System, quartzites, dolomites, and banded jaspers, and the Matsap or Waterberg sandstone, unconformably above these. The rocks present a bewildering number of correlation difficulties and nearly all the low-lying ground is covered with the red Kalahari sand which obscures the junctions of the several systems of rocks. There are no rivers or stream beds with the exception of the Orange River, and all the water precipitated in the rare rains sinks through the sand and evaporates slowly leaving behind a crust of calcareous sinter. Weathering therefore is of the desert type, and the breaking down of the rocks is nearly entirely brought about by expansion and contraction, without chemical change of the constituent minerals. For this reason the less compact Permian and Triassic clays and shales of the Dwyka and Ecca Series have yielded easily to the forces of destruction and have been blown away; the underlying rocks, however, of dense crystalline structure or of compact metamorphic nature, have emerged with relatively slight alteration from their burial beneath the Karroo rocks. The younger rocks were invaded by dolerite intrusions belonging to the great system of dykes and sills that extends right across South Africa almost from sea to sea, but the older are penetrated by a number of dykes of the most varying types which have been altered by crushing and metamorphic action generally so that they can be described as diabases, granulites, hornblende-schists, and serpentine with chrysotile. Besides these last there is a third class of intrusive rocks which is, paradoxically, amygdaloidal.

These amygdaloidal melaphyres are known throughout the region of the Palafric rocks, whether we trace them on the surface in the Colony, Bechuanaland, or the Transvaal, or encounter them

[1] *Ann. Rept. Geol. Comm.*, Cape Town, 1900; see also E. H. L. Schwarz, *Trans. Geol. Soc. S. A.*, Johannesburg, 1905, VII, and A. W. Rogers and E. H. L. Schwarz, "The Orange River Ground-Moraine," *Trans. Phil. Soc. S. A.*, Cape Town, 1900, IX.

in the depths in the mines of Kimberley. The main group of them occurs below the first member of the Transvaal Formation—the Black Reef Series—and was called by Molengraaff the Vaal River beds, but is now more generally known as the Ventersdorp beds. They consist of lavas of varying basicity ranging from melaphyres to felsites and rhyolites and are usually accompanied by enormous developments of agglomerate ranging from coarse boulder beds to fine volcanic ash.

Two areas of these amygdaloidal melaphyres occur in the Prieska district under discussion, while other and smaller areas are to be found in the neighborhood. The largest of the masses is found to the north of the district on the farm Zeekoe Baard; it wraps round the end of the range of hills called the Ezel Rand composed of Matsap (Waterberg) sandstone and separates these rocks from the granite to the west and partially interposes between them and the Keis or Black Reef quartzites. There is a small mass also lying apparently intruded in the Waterberg sandstone. On the south side of the Ezel Rand there are some steeply inclined beds of limestone and quartzite which look as if they were the basal beds of the great limestone series turned up by force from the direction of the center of the igneous mass. Toward the point of the Ezel Rand there are tracts of agglomerate which probably belong to the melaphyre. The southern extremity of the melaphyre is on the farm Geelbecks Dam where it tapers out; the greatest width of the mass is on the farm Blink Fontein where it is 9 miles across, and the extreme length is 30 miles. A large portion of the area mapped in as melaphyre is, however, covered densely with red sand, through which the rock only crops out occasionally; on Schalks Puts and on the eastern part of Blink Fontein there are conspicuous ranges of kopjes formed of the rock.

The melaphyre is in contact with the Keis (Black Reef) Series of the farms Ezel Klauw and Louis Draai on the north, and with the Matsap (Waterberg) beds of the Ezel Rand, which it surrounds on three sides. To the south it is bounded by the Campbell Rand (Dolomite) Series on the one side and the granite on the other. The field-relationships are not compatible with the supposition that the origin of the melaphyre was volcanic, unless a group of faults is brought in to explain the contact of the amygdaloid with such a large

range of rocks of widely separated ages; there is no evidence of such faulting, and although the rock is a typical lava, fine-grained to glassy in structure, and generally full of steam cavities, Dr. Rogers and myself were forced to the conclusion that the rock was an intrusive one and came into position after the earth movements affecting the Matsap beds had taken place.

About 30 miles in a southeasterly direction, reckoning from the southern extremity of the Zeekoe Baard mass, there is a second outcrop of amygdaloidal melaphyre on the eastern portion of the farm Jackals Water, and on the western part of the farm Prieska's Poort. The outcrop is elongated about 6 miles long and 1½ miles wide, trending northwest, the direction of strike of most of the Palafric rocks in the Prieska district. On the northeastern side the melaphyre is bounded by the granite of Prieska's Poort, and on the southeastern side by the Keis quartzites on the farms Jackals Water and Uitzigt.

Similar rocks in the neighboring districts which appear most certainly to be intrusive have strengthened the view that the Zeekoe Baard and Prieska's Poort amydaloids are instrusive, but against this we have the steam-holes and agglomerates—clear indications of volcanic origin.

If we accept the volcanic origin, then we must imagine that from a central vent or fissure some extremely fluid lava was poured out, which flooded all the low-lying country, wrapped round the hills, and finally cooled as a plain of lava. No known volcano fulfils these conditions, and from what we know of lava we would be inclined to state that such a mass could not be suddenly ejected at any one time, but would rather come up in separate flows, each of which would travel outward and downward and would cool long before it could wrap round the end of a range of hills such as the Ezel Rand, in the manner of a perfectly liquid substance. Then again we find the agglomerates at the periphery of the Zeekoe Baard mass, and here, also, to the north, there is evidence of thrust.

In whatever light we look upon these Prieska outcrops of amygdaloidal lava, confining our ideas to a terrestrial origin of the material, we come upon insuperable difficulties, but directly we admit the possibility of the fall of a meteor sufficiently large to melt up a portion of the earth's crust, all these difficulties vanish. The sudden develop-

ment of a large quantity of liquid lava, the permeation throughout of steam holes from water contained in the rocks melted, the ridging up of portions of the periphery of the mass, the absence of true volcanic ash, but the great development of crushed up material entangled in molten rock—all these phenomena receive an adequate explanation on the meteor hypothesis. That the masses of lava often tail out into apparent dykes can be readily accounted for from the fact that earth movements have gone on since the development of the lava and such dyke-like extensions would be portions drawn out by crushing just as a crystal of felspar is drawn out in many gneisses.

Against the general acceptance of such a theory there is the objection that certain of the Archaean and early periods are characterized by just such volcanic rocks as are to be found in Prieska, great masses of lavas and clastic igneous rocks of all sorts. If any of such volcanic areas owe their rocks to meteors, it is certainly probable that the masses of planetary matter were grouped in swarms which would produce the same effect on the whole as a general outburst of great volcanoes over the earth. Each swarm would gradually discharge the individual bolides as the earth in its course round the sun came within attracting distance, and when the swarm was exhausted or passed out of reach of the earth's attraction, then there would be a secession of the production of these igneous rocks and normal sedimentation would take place.

In conclusion I must repeat that I do not contend that I have proved the meteoric origin of the amygdaloidal melaphyres of Prieska; but I maintain that the facts that we now know force us to take into consideration, when dealing with these extensive tracts of molten material on the surface of the earth, their possible origin from the collision of large meteorites. Everywhere we look in the older rock systems, we find enormous deluges of igneous material which are difficult to explain on the theory that the mass came from the interior of the earth, such as, for instance, the Bushveld igneous complex in the Transvaal; the object of this paper is to point out a possible cause in many cases, which so far has not been recognized.

EROSION AND DEPOSITION IN THE SOUTHERN ARIZONA BOLSON REGION

C. F. TOLMAN
The University of Arizona, Tucson, Ariz.

Outline of Paper

Introduction

Physiographic Division of Arizona into Plateau and Bolson Country

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Topographical Features of the Bolson
- Rock surface
- Bajada
- Playa

Analysis of Geological Agencies under the Stimulus of Aridity
- Torrential precipitation
  - Theoretical analysis
  - Description of bajada building.
  - Factors affecting slope of bajada
- Wind action
  - Method of attack
  - The development of resistant pavements
- Underground water
  - Water level
  - Moisture table
  - Crust deposits

Climate. Discussion of the factors quantitatively important, and classification of the following types
- Type 1. Torrential precipitation dominant
  - Torrential concentration (extreme or moderate) in either case with daily temperature difference (extreme or large)
- Type 2. Protective plant covering controls
  - A moderate and distributed rainfall, with no great extreme of daily thermal range
- Type 3. Wind action important
  - A thin distributed rainfall grading to no rainfall, and daily temperature difference (extreme or large)

Deposits of the Bolson
- The bajada outwash. (*a*) Inclination. (*b*) Upper limit. (*c*) Size of material. (*d*) Shape of boulders. (*e*) Decomposition of material. (*f*) Sorting. (*g*) Arroyo trains. (*h*) Sand pockets. (*i*) Change in layers. (*j*) Stratification.
- Playa deposits. (1) Lake. (2) Standing water mud sheet. (3) Outwash mud sheet. Modifications induced by evaporation and wind erosion. Structure of the lake deposits. (*a*) Strands and terraces. (*b*) Distribution of coarse and fine. (*c*) Composition and lack of subaerial markings.

Structure of the playa muds. (*a*) Chemical deposits. (*b*) Surface markings. (*c*) Animal and plant remains. Erosion of the mud sheet.

CLIMATE AS AFFECTING THE EROSION OF THE BAJADA

Discussion of (1) the remains of an older bajada near Tucson, Arizona, and (2) the incision of the younger bajada by the larger gullies; showing that while climate theoretically might be competent, the facts of the case suggest that other conditions were the immediate cause of this erosion, and finally that climatic changes are better read in the detail of structure and composition of the deposits, rather than in topography.

INTRODUCTION

Before the publication of Barrell's studies on climate and deposition,[1] I wrote:

> It does not seem probable, therefore, that theoretical analysis of the complex relations that obtain between climate and deposition will accomplish what it has in the case of deposition by running water and by glacial action. The problem will be solved by detailed studies in each region. In each case the disturbing factors must be evaluated, and the intensity of each process gauged.[2]

The study of Barrell's article did not seriously affect the above opinion, but it did suggest and encourage the following contribution, on account of the evident value of his analysis in directing attention to the newly developing study of climatic effect on geological processes, in showing its possibilities, and in suggesting some of the criteria available.

In this contribution attention will be confined to a certain definite portion of the arid southwest, which is here called the bolson region. A criticism by Keyes of Hill's definition of the term "bolson"[3] and its use by Tight, Lee, and others gives point to an investigation of the history of the use of the word, and a discussion of its proper meaning.

The data to which this treatment owes its development have been collected during a residence in the arid southwest since 1901. The

[1] Joseph Barrell, "The Relation between Climate and Terrestrial Deposition," *Jour. Geol.*, 1908, pp. 159–90, 255–95, 363–84.

[2] C. F. Tolman, "The Geology of the Vicinity of Tumamoc Hills," *Publication 113*, The Carnegie Institution of Washington (in press).

[3] Hill, *Topographic Atlas of the United States*, U. S. G. S.; Keyes, "Bolson Plains and the Condition of Their Existence," *Am. Geol.*, Vol. XXXIV, pp. 160–64; "Bolson Plains," *Am. Jour. Sci.*, Vol. XV, pp. 207 ff.; "Rock Floor of the Intermont Plains of the Arid Region," *Bull. Geol. Soc. Am.*, Vol. XIX, pp. 63–92; Tight, "Bolson Plains of the Southwest," *Am. Geol.*, Vol. XXXVI, pp. 271–84.

earlier portion of this time was spent in constant traveling over southern Arizona, and northwestern Mexico. In order that the value of the observations and deductions presented may be approximated, it is frankly admitted that until recently attention was not directed to the broader features of desert physiography. The attitude of mind, bent on the study of the details of ore deposition, and therefore investigating minor features so important in that study, was carried over to the examination of the sedimentary deposits, and details of texture and structure, and their possible explanations were readily noticed. It is believed that such a study, undertaken systematically, however, will reveal the intimate relation between climate and deposition.

PHYSIOGRAPHIC DIVISIONS OF ARIZONA

Arizona has been divided into the plateau region, the range region, and the volcanic region by Gilbert, and later by Ransome into the plateau region, the mountain region, and the desert region.[1] A twofold division is preferred for the purposes of this paper, the separating line being the great Mogollon escarpment and its extensions, as shown on Robinson's map of the Colorado Plateaus.[2] The northern portion is designated as "the mesa or plateau region," and the broken area to the south the "bolson" country. The plateau region will not be under consideration, the student being referred to the unsurpassed descriptions of Dutton, and the recent work of Robinson and Lee.[3]

The generalization that this southern region is an intricately broken-down portion of the central plateau is remarkably true considering the broadness of the statement, the regularity of the broken fault-blocks, however, is modified by the complicated post-Carboniferous intrusive masses. Further the form of the secondary hills is

[1] Gilbert, "Report on the Geology of New Mexico and Arizona," *U. S. Geol. and Geog. Survey of the 100th Mer.*, Vol. III; Ransome, "The Geology of the Globe Copper District," *Prof. Paper 12*, U. S. G. S., pp. 14–16, with map.

[2] Robinson, "Tertiary Peneplains of the Plateau District," *Am. Jour. Sci.*, August, 1907, p. 123.

[3] Dutton, "Tertiary History of the Grand Canyon Region," *Mon. II*, U. S. G. S.; Robinson, *op. cit.*, pp. 109–29; Lee, "Geology of the Lower Colorado River," *Bull. Geol. Soc. Am.*, Vol. 17, pp. 275–85.

often controlled by a mosaic of small fault-blocks, showing a remarkably close relation of hills and gullies to blocks and faults. Toward the south and southwest, the fault-blocks develop into parallel strips; ridge after ridge of Paleozoic limestones, and successive sheets of rhyolitic and andesitic lavas rear their heads above the desert-filled wastes. These fault-strips, rather than fault-blocks, are well developed southwest from Casa Grande, the steep scarps facing northeast, and the faults striking northwest, the most important escarpment being that of the Vekol Mountains where several thousand feet of Carboniferous strata are exposed, with an unusual development of upper arenaceous members. The waste between the hills consists of wash deposits, volcanic deposits, playa deposits, and occasional lake deposits, this complicated series dating back through the Quaternary and probably the late Tertiary. Sufficient data have been collected by scattered observations to indicate that in their structure they show the effect of various conditions of climate and topography, and give color to the belief that the history of the Quaternary at least will be discovered by a well-directed reconnaissance of the region.

DISCUSSION OF THE TERM "BOLSON"

With the above description in mind, it is evident that southern Arizona is a region of bolsons, as defined by Hill. He states:

> The bolson plains . . . . are newer and later features consisting of structural valleys between mountains or plateau plains, which have been partially filled with débris derived from the adjacent eminences. [1]

Keyes strenuously objects to the application of the term so defined to the New Mexican examples. He states that the Jornado del Muerto, and Estancia plains are valleys showing erosion bevelment, and are not structural, and that they have but a thin veneer of desert waste.[2] Going farther, he states that New Mexican plains are in general destructional planes, in soft Cretaceous strata with only a thin capping of desert waste, and by assumption these conditions are extended to cover Arizona bolsons. Tight has taken exception to these conclusions as applied to New Mexico, and certainly in the structurally broken country of southern Arizona, the deeply filled,

[1] *Op. cit.*, p. 8.

[2] *Op. cit.*, pp. 66, 67.

undrained, or feebly drained areas, corresponding to Hill's definition, exist par excellence. Here there is little danger of confusing soft Cretaceous strata with the later fill.

The following list showing the depths of a few typical wells in the southern bolson region is compiled from a large number of logs furnished me through the courtesy of the Southern Pacific engineers and others. As the wells are sunk only to a good flow of water, the depth of the fill is not known in any case. The Esmond[1] well is especially interesting, as it is situated toward the eastern edge of the semi-bolson of the Tucson District, about five miles from the nearest rock slope, and yet it shows 1,480 feet of typical outwash material. These wells indicate surely more than a "thin veneer" of detrital outwash.

Well	Depth. Feet	Character
Safford S. P. well.....	1,820	Bolson lake beds
Benson S. P. well No. 2...	717	Chiefly bolson lake beds
Benson S. P. well No. 3...	806	Chiefly bolson lake beds
St. David's Artesian well....	530	Chiefly bolson lake beds
Esmond S. P. well	1,480	Tucson semi-bolson deposits
Gila S. P. well.....	1,386	Semi-bolson. Lava flow from 1,250 to 1,290
Casa Grande S. P. wells...	615 625	A semi-bolson in Santa Cruz drainage in a region of typical bolsons
Sentinel S. P. well, No. 1..	1,129	Showing 1 lava flow in section
Sentinel S. P. well, No. 2..	962	Showing 2 lava flows in section
Sentinel S. P. well, No. 3..	1,082	Showing 2 lava flows in section and all three are typical wash deposits of a semi-bolson region
Wellton S. P. well.....	1,120	A semi-bolson near Colorado River

The word "bolson" of course is of Spanish origin, and its application by the early Spanish settlers and their descendants shows a keen eye for topographic forms, painfully lacking in the later American invader, who with perfect unconcern will, for instance, designate the surface of a topographic basin as a mesa (a table).

In looking over a collection of old maps of the southwest at the Carnegie Desert Laboratory, I find that "Bolson Mapimi" appears on Thompson's *New General Atlas No. 50*, published in 1814, and since then the word has been in continuous use as a technical geographical term. Hill's definition is faulty in that it imposes a restriction which is only possible of application after the geological structure

[1] *Publication 99*, The Carnegie Institution of Washington, pp. 58, 59.

of the region has been worked out, and not justified, considering the great priority of the Spanish usage.

The geologist is not the only one that has a right to be heard in this matter, for the problems of the desert are being attacked enthusiastically and successfully by the botanist, and it is only by the combined action of the two that the broad problems of desert history and climate will be solved. There is a need for a word by which the individual self-centered drainage systems of the desert can be designated, and we should return to the original and broader meaning of the word bolson. I therefore suggest that the word be used to cover the watershed of a centripetal drainage system, including all the area within the limits of the divides.

The bolson may depart somewhat from a perfect topographical basin, for evaporation on a slope may prevent the development of a through drainage, and foster the centripetal variety. Those bolsons whose surface water *in times of flood* reaches some river thoroughfare, some lower bolson, or the ocean direct, and consequently the playa portion described below is poorly developed or lacking, may be called semi-bolsons. In Arizona, therefore, there is every gradation between bolson, semi-bolson, and ordinary river drainage, the latter becoming more prominent as the Colorado River is approached.

TOPOGRAPHY OF THE BOLSON

The well-developed bolson presents three distinct topographic features. (1) *The Upper Rock Surface.*[1] The slope of this surface is a function of rock structure and composition, and erosive attack. The top surface may be a mesa, developed either on account of protective action of some hard layer, or an older erosional flat, which on the top of the higher mountains is protected on account of the forest growth.[2] The latter are so discontinuous that they have as yet defied any general correlation, and the discovery thereby of a faulted peneplain. (2) *The bajada.* Extending down from the rock surfaces are the flanking detrital slopes,[3] built up by terrestrial

[1] Tolman, *loc. cit.*, gives photographs and diagram illustrating bolson topography.

[2] Example, top of Catalina Mts., north of Tucson, Arizona.

[3] Blake, "The Flanking Detrital Slopes of the Mountains of the Southwest Portion of the United States," *Science*, new series, Vol. XXV, p. 974, states conclusions at variance with those presented here. Probably the best descriptions of all the different features of bolsons are found in Carnegie *Publication 26*, "Explorations in Turkestan."

deposition, the aggradational equivalent of the active erosion above. These slopes are the dominant feature of the arid landscape, each mountain range (or isolated hill under severe climatic conditions) appearing to stand on a symmetrical pedestal. The novelty of these features, and the prominent and distinct place they hold topographically, have led to a repeated request for a formal name. In a former publication already referred to, I recommended the use of the term "slope," describing each particular incline by the name of the mountain which gave it birth: viz., Tumamoc slope, Catalina slope, etc. The difficulty of preventing confusion between the detrital slopes and the rock slopes of the mountains brought out the necessity of a new name for this feature, for which the Spanish word *bajada* has been selected, local usage almost exactly corresponding to the technical meaning suggested. (3) *The playa.* Finally in the well-developed bolsons, there is a central flat, or flats in the irregular and larger bolsons, which is occasionally or even permanently occupied by a water sheet, the life of the temporary lake or pond depending on local climate conditions. In less perfect examples of the semi-bolson this central feature is lacking. In such a bolson, especially where large, the central portion may be a more or less irregular plain, composed of river, outwash, and other deposits, and the general name to be applied is "bolson plains."

ANALYSIS OF GEOLOGICAL PROCESSES IN ARID REGIONS

Torrential precipitation.—Before attention is directed to the aggradational deposits of the bajadas and playas, a preliminary investigation is advisable regarding the action of geological processes under the stimulus of aridity. It is generally assumed that all the precipitation of the desert regions is of torrential character. This is the exaggerated recognition of the fact that there is a marked tendency in that direction, and even where a given shower has no greater density than one in humid region, the run off is more rapid, and torrential concentration accentuated.

Assume a moderately arid region, with a marked tendency toward torrential concentration of precipitation, with both a large daily thermal swing (marked difference between day and night temperatures) and an active wind transportation and deposition. The coarse

material is pried off and made ready for the attack of torrential stream by daily temperature change, and the fine material is brought up by the wind. There is no grading in size between the two, the deficiency of material of intermediate size being marked.

Under the well-known erosion analysis in the case of "a homogeneous island with one depression" let any flood encounter a depression of any kind accelerating its flow, then there *must* be a gullying started which will work up stream. Now the sheet flood described below often flows over irregular ground, and even then its gullying action is almost entirely lacking. The observation of this phenomenon led to an investigation of the manner in which material is transported by flood action. It has not yet been possible to check observation with experimental data, but on account of the bearing on the problems at hand, I present the following inspection of certain phases of this transportation.

Sediments are carried forward by running water in the following three ways: (1) The large material is rolled on the bottom; (2) Finer material is thrown up and down by subcurrents, drifting forward with the current; (3) The superfine is held in suspension by the kinetic action of inter-impact.

1. As is well known the mass of the largest particle that can be rolled on the bottom varies approximately as the sixth power of the velocity of the stream at its bottom. The material rolled comprises the cutting machinery of the stream, and the fact that the size increases so rapidly with quickening velocity, gives to the stream its great power of concentration of energy at declivities and at the down-stream side of hard strata. If a stream is in the rather unusual position of having no coarse material to roll on its bottom, it will not only not be able to cut hard rock, but it will have nothing with which to stir up the finer material in its channel, and therefore its cutting power is reduced.

2. The intermediate and fine material is danced upward by the secondary currents, eddies, etc., of the stream, and during its up-and-down journeys it is carried forward by the current. The formation of these eddies is generally recognized[1] and they are shown in an impressive way in the eddies and whirlpools of the sullen mud-laden floods of the southwest. The whirls are formed by friction both

[1] See Chamberlin and Salisbury, *Geol.*, Vol. I, pp. 111, 112.

along the bed of the stream, and between the layers, as shown in Fig. 1. The bottom whirl can probably be considered of primary importance, because (*a*) at the bottom there is the greatest friction, and therefore, the greatest difference of velocity; (*b*) the bottom whirl has an unbalanced upward velocity: (*c*) the higher whirls have equal upward and downward components, and can affect only the material they have received from the bottom whirls. They will accelerate the upward motion of some particles and retard others to the same extent. Therefore in this preliminary inspection the action of the bottom whirls only is considered. Although the motions will be complex, assume a certain whirl which represents the average upward throw of the stream. Increase the velocity of the stream and the subcurrents will increase presumably approximately directly as the velocity of the stream.

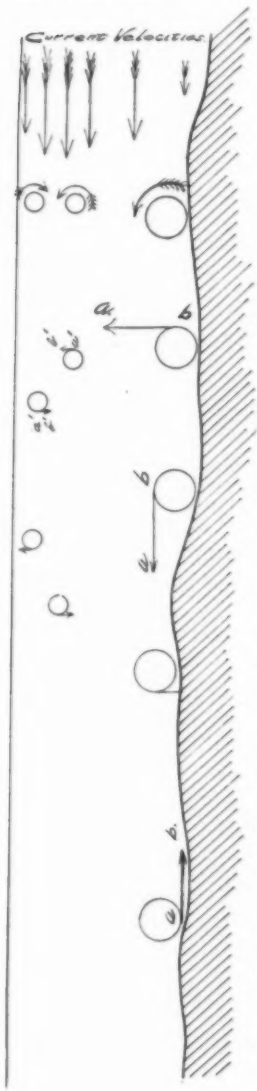

FIG. 1.—The current velocities are indicated at the right. The throw of the bottom whirls is indicated by the arrows *a*, *b*. The small intercurrent whirls have balanced action and receive material from the bottom whirls, and are not important.

Following the course of events as they commonly occur in arid regions, let us assume that the sudden shower or cloudburst picks up a great load of both coarse and fine. Let this shower be on the rock slope of a bolson. There is no dropping of coarse and picking-up of fine material as is postulated for the ordinary stream, because mountain-slope and torrential concentration give a great excess of energy, so

that everything loose on the surface is swept down into the steep canyon. The grade of the canyon decreases below, and deposition commences, boulders first and the rest following in decreasing size according to the v^6 formula for mass to velocity. Here the ordinary backing-up effect is not important. Permanent streams generally develop deposition at a certain point, and this works back, the current damming itself up. The torrent, however, drops its coarse at the top and the rest continuously on its downward path, resembling a single wave rather than a continuous current, so that the effects of deposition are not readily transmitted backward. Wash deposits often show simultaneous dropping of coarse and fine together, as a result of rapid checking of velocity, the formation consisting of a conglomerate of pebbles or boulders set in a matrix of sand or mud, the boulders carried down by the deepest rush of the torrent, and filled in with sand by the subsiding water. Such a deposit indicates clearly the agency of torrential flood. Farther down there may be a spreading-out of the flood as a widening sheet of mud and water. This is the flood sheet, and it may be either the expanded lower portion of the torrent from far above, or the even sheet of run-off from a shower on the lower detrital slope. The coarse material has been dropped, and the fine is now carried wholly in suspension.

The ordinary conception of a loaded stream is one that is picking up material to its full capacity, and also one that has the fine material at hand so that the picking-up and the laying-down are in equilibrium. To increase the capacity of a stream to carry material in suspension therefore, it is necessary to increase either (*a*) the number of bottom subwhirls, or (*b*) the number of particles cast upward in unit time by each subwhirl, or (*c*) the average upward throw of the bottom whirls.

Let these factors be represented respectively by m, n, and d, and L the carrying capacity of a stream for fine material suspended by subcurrents.

(1) $$L \propto mnd.$$

We have assumed certain whirls distributed over the bottom, representing the average upward throw of the stream, and that fine

material of a single size is being transported; therefore m can be considered a constant. Both n, the number of particles thrown upward, and d, the distance of throw, depend upon the velocity of subwhirl, which was assumed above (on account of lack of experimental data) to vary approximately directly as the average current velocity,[1] or

$$L \propto v^2. \tag{2}$$

Assume that in the tumultuous advance of the flood sheet, the average throw of the subwhirls is equal to the depth of the stream (Fig. 2, *A*), then an increase in the velocity (due to some irregularity in its path) cannot increase d (Fig. 2, *B*), because the particles cannot

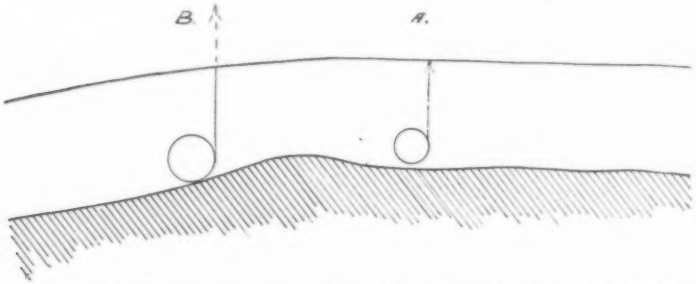

FIG. 2.—A. The average upward throw of the bottom whirl is equal to the depth of the stream. B. The average upward velocity imparted by subwhirl is greater than that necessary to take the particle to the surface.

be thrown above the surface of the water. Therefore under these conditions

$$L \propto v. \tag{3}$$

This shows only a very moderate increase in carrying capacity, not at all comparable with the effect of current velocity on the power to *roll* material forward, which seems generally to have been assumed to govern the eroding power of a loaded stream on receiving an increase in velocity.

In the above analysis, it was assumed that the material shot up by the whirls sinks downward undisturbed by other currents. As a

[1] The Colorado River offers excellent opportunity to study the difference in velocity at various depths in times of flood when silt laden, and in times of clear low water.

matter of fact the whirl must produce upward and return currents. Therefore the effect of increased subwhirl velocity in shooting up a larger number of particles will be in part balanced by a more rapid downward journey of the same particles due to the increased velocity of the complementary return currents. Therefore

(4) $L \propto$ less than directly with v.

Will, however, this moderate increase in power to suspend material be effective under the conditions that obtain in the arid southwest? Is there loose material to pick up? Is equilibrium easily established between the material in the stream and the material on the ground over which it passes? The flood is advancing over a surface that (1) may be a baked mud flow, or (2) is cemented by desert salts, or (3) is protected by pavements described later; therefore it cannot cut, for its tools have been laid down above, and it cannot pick up loose material, for that has been swept away by the wind.

3. It has been suggested to me by Dr. A. E. Douglass, of the University of Arizona, that the finest of the material is not suspended by the subcurrents, but that due to the difference in velocity in the various layers of the water, the numerous superfine particles are in constant collision, and the kinetic bombardment (like that of solutions ascribed to heat) causes a diffusion of particles upward from the region of greatest velocity difference, viz., the bottom. Further, it is to be suspected that the attached air bubbles aid in the suspension of the emulsion, for after boiling a mixture of very fine loess, Dr. Douglass found that the cloud of particles did not rise as readily upon rotating the containing vessel as before. The increasing power to suspend superfine material from the increase in declivity will not cause noticeable erosion, however, on account of a lack of loose fine material of this nature.

We may conclude therefore that a flood sheet is far less responsive to moderate increase of gradient, than an ordinary stream. It is a depositing and not an eroding agency and will not develop into the former even when subject to a moderate increase in current velocity.

As the flood sheet advances its velocity is checked (1) by evaporation, to a minor extent, (2) by absorption in the ground, and (3) mainly by spreading out to a thin sheet, thus greatly increasing surface

friction, the final layer of mud being left at or toward the bottom of the slope.

I have described the ideal case in which the descending water spreads out into the flood sheet. This particular phase, described by McGee, and emphasized by Keyes,[1] while not uncommon, has hardly the importance attached by those observers. It is in every case a depositing and not an eroding sheet, save when confined to a valley where it can do some undercutting, and it is strange that the term "sheet-flood erosion" should have been allowed to go unchallenged so long in geological literature. Final deposition on the margins of the bajada is more often by distributaries, as described by Johnson,[2] although again his statement that the latter is the only method is not in accord with the conclusions reached here.

In any case torrential action develops the three topographic surfaces mentioned above. The occasional storm will accomplish more work, in comparison to the precipitation involved, than more frequent cloudbursts, as the first can carry off the entire supply, leaving the following storms to rework its deposits. Provided that there is no marked change at the foot of the slope, such as earth movements affecting the same, damming-back of the bajada drainage by expanded water sheet, or a quickening of the temporary "through drainage," in the case of the semi-bolson, the initial angle of deposition depends upon a number of minor factors, a few of which are stated below in about the order of their relative value: (1) *Size of abundant fragments.* The relation of upper slope to the coarse material occurring in large amounts, is noticeable everywhere; (2) *Density of precipitation,* and (3) *Supply of detritus.* The largest bajadas should be developed with steepest initial slope where concentrated torrential precipitation is separated by intervals of sufficient time for the development of a large supply of detritus; (4) *Height of mountains above foot of bajada.* Attention will be again turned to the upper margin after climate has been analyzed.

Wind action.—The wind has been given the leading rôle among

[1] McGee, "Sheetflood Erosion," *Bull. Geol. Soc. Am.*, Vol. VII, pp. 87–112; Keyes, *op. cit.*, pp. 78–82.

[2] Johnson, "The High Plains and Their Utilization," *Twenty-first Annual Report* U. S. G. S., pp. 612–22.

the physiographic agencies in regions of aridity, by some authorities, while others have given it an intermediate or even a minor importance. The fact is that wind plays a varying rôle from major to minor depending upon the variety of arid climate. This is investigated later and attention is now directed to the method of erosive wind attack and the resistant surfaces developed thereto.

It seems to be commonly believed that wind may attack successfully an unelevated or even a depressed flat surface.[1] It is true that the wind picks up most of the fine material it transports from flat lowlands, but this is largely a repicking of material dropped; of tourist-passenger particles on a stop-over ticket. The source is from certain limited areas that are undergoing erosion on account of special exposure and non-protection.

The larger portion of the surface of the southwestern arid region is fortified against the attack of the wind by desert pavements. Take as an example of extreme development those north of the Chocolate Mountains and west of the Colorado River, protecting an old flood-plain deposit of the latter stream. There the surface is covered with a perfect mosaic of fitted stones, polished and flattened to the last degree of perfection by the wind. The light of the early or late sun is thrown back from uncounted faceted mirrors, in a dancing blaze. Step on this pavement and you are surprised to find the apparently solid rock yielding underfoot. Scratch it with your boot, and you find that there is only a single thickness of pebbles, in size up to an inch in diameter, and at times less than a quarter of an inch thick, covering a deposit of hot, dry dust. A few trips of the wagon in the same tracks, will form deep ruts by the breaking of the pavement. The above description is of the most perfect pavement I have seen, but everywhere, except in the sorted sand of the dune regions, a strong wind develops resisting pavements. The wind attack upon a deposit of dry playa mud, mixed with occasional pebbles (such pebbles are common to all deposits on account of the vicissitudes of arid deposition) must proceed as follows: First (provided no crust deposits interfere), the wind can blow just as much dust as contains on the average a single layer of pebbles; second, this layer of pebbles

[1] Davis, "The Geographical Cycle in an Arid Climate," *Jour. Geol.*, 1905, pp. 385, 388, 391.

must be laboriously sandpapered to nothingness, before the second layer can be touched. MacDougal[1] reports that wheel tracks were seen on his trip into Lower California, that had been made sixteen years ago, and that the gun ruts of the Walker Filibustering Expedition are reported to be still visible in places after fifty years. In fact, a wheel track on such a pavement as is described above would last indefinitely according to ordinary popular measurements. The polishing of a horizontal surface is striking, but the erosion accomplished by this action can easily be exaggerated. The wind motion is nearly tangent to the ground, and the sand is danced lightly off a flat surface. Let a projecting face withstand the wind, however, and it immediately concentrates its energy to the work as vigorously as a youthful river to an opposing hard stratum. The maximum work is done where a crumbly horizontal sandstone attempts to withstand the wind. Here no talus protects the face of the cliff, and the opposing strata are completely chiseled off before the blast.[2]

The wind will undercut by working in the least resistant layer, the amount of this carving being limited by the talus from the harder layer above. Even the talus, however, is exposed to the windblast, and its removal may be assisted by torrential water, and yielding rapidly or slowly allows fresh attack on the cliffs.

A study of almost any erosion forms in an arid country shows undercut wind action, and further description is unnecessary. The action being most effective against vertical faces of horizontal strata, the wind terraces are driven back along the weak layers. There can be no question but that much of the amphitheater work of the Grand Canyon of the Colorado, and the level steps of the high plateaus of Arizona and Utah are developed by wind erosion.[3]

Underground water.—The depth at which underground water is encountered in bolsons is very variable. Considered in relation to surface geology, however, interest is not so much attached to the underground water table as to the surface moisture table. Recent

[1] MacDougal, "Botanical Features of North American Deserts," *Publication 99*, Carnegie Institution of Washington, p. 96.

[2] Whitman Cross, "Wind Erosion in the Plateau Country," *Bull. of the Geol. Soc.*, Vol. XIX, pp. 53–62, a striking example of the above.

[3] Keyes, *op. cit.*, pp. 81–83, 85–91, an extreme estimate of the importance of wind erosion.

experiments in dry farming show how a moisture table, elevated far above the water level, can be developed and protected by cultivation.[1] The crust deposits of the semiarid regions are believed to be developed by a similar moisture table. The rainwater penetrates with difficulty the dry soil, and while a portion may gain the larger openings and sink to the underground water level, a larger portion is caught in the capillary pores and drawn upward by the drying-out above, and laden with mineral salts deposits its load as the "caliche" crusts,[2] through evaporation at or near the surface. These crusts are built into the deposits, and are slowly recrystallized, forming the calcareous, gypsiferous, and even siliceous cement of the cement-gravels. The well sections examined in the vicinity of Tucson show that the amount of the cemented gravels may rise to 80 per cent. of the whole. Possibly the "mortar beds" of the high plains of Kansas, for which Johnson could find no adequate explanation[3] were surface crusts formed under local conditions of aridity, by means of an actively evaporating moisture table, and covered by subsequent deposits.

CLIMATE

I believe that in the future, when the recognition of climatic effects in sedimentation becomes general, the value of the recent articles by Barrell and Huntington[4] will be highly rated. Climate itself, however, needs still further analysis before its effects can be read satisfactorily in the strata. The critical factors from the erosional and depositional standpoint have not yet been determined, especially those that are in a measure the independent variables, nor has the

[1] See *Bulletins 103* and *130*, Bureau of Plant Industry; also Livingston, "The Soils of the Desert Laboratory Domain," *Publication 113*, Carnegie Institution of Washington; *Bulletin Agricultural College of Utah, No. 91;* Alway, "Studies of Soil Moisture in the Great Plains Regions," *Jour. Agricultural Science*, Vol. II, pp. 333–42.

[2] For description and discussion of the caliche see Blake, *Trans. Am. Inst. of Mining Engs.*, Vol. XXXI, pp. 220–26; Tolman, *loc. cit.;* Lee, *Water Supply Papers, No. 136*, U. S. G. S., p. 111.

[3] *Op. cit.*, pp. 643–57.

[4] Barrell, "The Relation between Climate and Deposition," cited above; "Relative Importance of Continental and Marine Sedimentation," *Jour. of Geol.*, Vol. XIV, 1906, pp. 316–56, 430–59, 524–68; Huntington, "Some Characteristics of the Glacial Period in Non-Glacial Regions," *Bull. Geol. Soc. Am.*, Vol. XVIII, pp. 351–85.

effect of the swing from one kind of climate to another received more than introductory treatment at the hands of Barrell.

Climate is the product of complex causes, a few of which may be considered the critical factors, and the rest quite subordinate. Barrell's classification of climate into warm and cold humid, and warm and cold arid, or again into constantly rainy, intermittently rainy, subarid, and arid, group together certain more or less decided expressions of climate, the fundamental factors of which may vary considerably, and, moreover, under the present practice of compiling weather data, these differences, some of major importance, could not be detected. The present unsatisfactory state of climatic analysis may be realized by comparing the conclusions of Barrell and Huntington in regard to the climate oscillations in regions outside the ice-sheets during the glacial epochs. Barrell suggests that in certain regions increasing cold may increase rock disintegration, without a corresponding increase in the transporting power of the streams, and therefore the outwash deposits may have been built up steeper as a response to the increasing cold of the glacial period, and on swing to a warmer climate there was erosion.[1]

Huntington explains that in the arid regions of Asia the moist (glacial) epoch accelerated the weathering of rock and growth of vegetation. Therefore waste was stored in the upper valleys of the mountains. Aridity followed with torrential precipitation and the destruction of vegetation, therefore the stored material was washed down on to the bajadas, and later, the supply from above giving out, these outwash deposits were dissected. Therefore each swing from glacial to interglacial is represented by a terrace.[2]

In reaching these different results in regard to the glacial-interglacial swing in elevated subarid regions, different sets of critical factors are assumed. It is not unlikely that both assumptions are correct and that the variations in different factors occurred at different times. It surely therefore is profitable to find out if possible what factors are of quantitative importance, and what range of play is possible between them.

[1] *Op. cit.*, pp. 172, 173. Barrell applies this to the dissection of the Gila Conglomerate. The author has reached a different conclusion which he hopes to present in a later contribution.

[2] *Op. cit.*, pp. 357, 358.

We must assume that there are certain areas of the globe which have had a dominantly arid climate as long as the atmospheric and oceanic circulation and the shape and relief of the continents resemble that of today. Doubtless those tracts whose arid condition is due chiefly to the trade winds have had a more continuous and a more steady arid history, than the deserts of the northern regions due mainly to topography. We have had the curious anomaly in the development of a geological philosophy during the last twenty years permitting, on the one hand, the upthrust of a continent thousands of feet, on the evidence of a slightly river-scarred plain, and, on the other hand, an almost universal assumption of climatic constancy, that could not possibly exist in view of the movements involved. Fully as curious are the physics involved in the earth movements necessary to make the lakes hold water, and then discharge the same again, in which the shifting piedmont and outwash deposits (erroneously interpreted as lacustrine) have been assumed to be laid down.

In the bolson region it is believed that if only there is a general dominance of arid conditions, a very considerable swing from arid to humid and back again is permitted. The through drainage of the moister climates has had great difficulty in cutting through the great talus and rock slopes which aridity has carved and built up into undrained basins.

While aridity depends primarily on deficiency of precipitation, variations in the same may take place along the following lines:

TYPES DEPENDING UPON THE DISTRIBUTION OF PRECIPITATION

Type 1. Torrential concentration of rainfall: (*a*) with moderate rainfall; (*b*) with deficient rainfall.

Type 2. A distributed and gentle rainfall, moderate in amount.

Type 3. A distributed and gentle rainfall very deficient in amount.

Torrential concentration.—The importance of torrential precipitation need not be investigated here. All writers are unanimous in giving it an important rôle. The general assumption seems to be that torrential concentration increases with aridity. It should be emphasized, however, that we have not the observational data to properly gauge this factor. The weather bureau arranges its data along *average* lines. Average daily, weekly, monthly, yearly tables

are given and doubtless later we will be told the average of the century. A knowledge of the average precipitation tells us little. The observations should also be arranged to determine the density of the precipitation, the unit taken being a rate of fall measured in centimeters per hour, then the figures for the rate of fall of each shower, or the most violent portion of the same would furnish some numerical foundation for further deduction. The assumption that increasing aridity always involves increasing torrentiality is not wholly justified, for conditions can be set up deductively which will cause an increasing precipitation of increasing torrential character.

In this preliminary analysis, therefore, torrential concentration is chosen as the first of the important factors governing desert climates. Livingston reports[1] that summer rains in Tucson often reach the amount represented by 1 cm in ten to fifteen minutes, and I estimate that, under the conditions that there obtain, a density of 3 cm per hour can probably be considered the lower limit of torrential precipitation.

The climate of the Salton Sink and San Felipe desert in Lower California is a good example of Type 3. MacDougal states[2] that the rainfall is distributed through the year so that only a small precipitation is received within any one month, and that at the Raza Islands no precipitation occurred for more than an entire year. At Fort Yuma the average for twenty-six years is 2.84 inches per year, with a fairly even monthly distribution, excepting a notable decrease for April, May, and June. This region shows to a marked degree the increased importance of wind action, and the extensive slopes are of gentler gradient than those developed under more torrential conditions. Without carrying analysis farther it is safe to conclude that under a non-torrential and distributed precipitation, the main quantitative factor is the increase in the relative importance of the wind action.[3]

If now rainfall increases moderately without decided torrential concentration, it is probable that vegetation, especially the grasses and the forests, will increase in importance, and the material of rock disintegration is held back, chemical weathering starts, talus slopes

[1] *Loc. cit.* [2] *Op. cit.*, p. 43.

[3] See Douglass, *The Crescent Dunes of Southern Peru* (in press); (Tolman, "The Crescentic Dunes of the Saltan Sea," *Jour. of Geography* (in press).

decrease in inclination, and also are protected against removal by grasses.[1] Here then the factor of increasing importance is the protective sheet of vegetation.

Effect of temperature.—Here again the extreme *daily* difference in temperature at the naked rock surface is desired, and the abundant data compiled from observations taken under shelters, etc., are of little value. Further, in the attempt to discover those factors of primary importance, all changes of longer period may be overlooked. Where the freezing-point is crossed daily, we probably have one of the maximum points in temperature change action, and where the rock surface remains above or below freezing for more than a day, the effect is diminished.[2] Here again there is a chance to gather further information, at moderate outlay of trouble, by placing self-recording thermometers on exposed rock surfaces, at different altitudes and times of the year in desert regions. It is evident that daily temperature is a variable, at least partially independent of the distribution of the rainfall, and after data have been collected its separate analysis as a climate factor should be attempted. Summing up we find that the following varieties of desert climate are important:

Type 1. Torrential Precipitation Dominant

Torrential distribution... { A—extreme / or / B—moderate } { in either case / with daily temp. diff. } { *a*) extreme / or / *b*) large }

Type 2. Protective Plant Covering Controls

A moderate and distributed rainfall with no great extremes of daily thermal change.

Type 3. Wind Action Important

A thin distributed rainfall grading to no rainfall. { and daily temp. difference { *a*) extreme / or / *b*) large }

DEPOSITS OF THE BOLSON

The Bajada Outwash. Inclination.—In the moderate torrential conditions of southern Arizona, the middle portion of the slopes varies from 50 to 300 feet per mile. The grade of this middle portion appears remark-

[1] Johnson, *op. cit.*, p. 625.

[2] See Barrell, *op. cit.*, p. 172, for a summary not entirely in accord with the above and for a list of authorities; also C. and C., *Geology*, Vol. I, pp. 44–48, and MacDougal, *op. cit.*, pp. 77–79.

able even to the eye, and shows on the topographical maps by the even spacing of the contours. The grade increases on approaching the rock surface, and in extreme cases, especially where the slopes lead up to volcanic hills where undersapping by wind is prominent, it approaches the angle of repose for the material of which it is composed. It is distinguished from the upper margin of lake and ocean deposits by the absence of wave-built and wave-cut terraces, and the flat upper surface of the top set of the delta, etc.

Upper limit.—The line traced by the contact of the detrital material with the rock surface invariably extends up every gully and down around every ridge. With lake or ocean deposits a level upper line is scarred into the landscape by beach and cliff action.

Size of material.—The astonishing size of the boulders found in the outwash, with other phenomena described later, has led to a local popular appeal to glacial action. Boulders up to six feet in diameter are found in the Catalina and Santa Rita outwashes near Tucson, for a distance of half a mile from the present rock surface, and boulders at least two feet in diameter six miles and more from the present ranges. In ocean deposits occasional distribution of material of this size below cliffs only is noted.

Shape of boulders.—They are generally subangular, although some are partly rounded by their tumultuous journey.

Decomposition of the material.—Almost no decomposition of either boulders or smaller material was noted in the various bajada deposits examined; so much so that grave difficulty is encountered when attempting to account for the large amount of calcareous cementing material often present.

Sorting.—Layers of sized and clean sorted boulders, gravel, and sand are discovered but more often sorting is completely lacking, although stratification is always excellently developed. Pebbles are found in a matrix of sand, and boulders in a matrix of clay. In extreme cases the latter may not be due to water action. For instance, about two miles northwest of Travertine Point, Salton Basin, California, talus deposits, remnants of old slopes, were filled in with wind dust, and proved treacherous to climb. This is a deposit formed under extreme conditions of great daily temperature change and small non-torrential precipitation.

Arroyo trains.—The larger streams often run, for a portion of their course, at least, below the surface of the bajada, and nevertheless their work may be on the whole aggradational. Down such channels the streams bring large boulders, forming extensive radial deposits of rock trains.[1]

Sand pockets.—In the larger stream bottoms, especially in the cross drainage when developed at the foot of the bajada, deposits of perfectly sorted sand occur in "whirl pockets" sometimes composed of clean mica, forming then bad quicksand deposits.

Changes in layers.—The shifting character of the aggrading streams records itself in the rapid wedging-out of the layers. This is especially well shown in Tucson well sections where the boulder layers in adjacent wells do not occur in the same place in the column.

[1] Tolman, "Notes on Desert Processes and Desert Deposits," *Journal of the Proceedings of the Annual Convention of the Arizona Miners Association*, 1905–6, p. 15: "The distribution of coarse material in the outwash desert deposits is in some ways remarkable. The larger stuff is, of course, somewhere in the vicinity of the mountains. It is also distributed to great distances down the temporary torrent channels. To appreciate what is accomplished in these waterways at a distance from the mountains, it is necessary for one to have seen some such a display as I once witnessed on the desert plain between Altar and Puertocito on the road to Santa Ana, Sonora, Mexico. I was driving with no thought of rain, when suddenly I came to one of the numerous washes that cross the road, and found it filled to the brim with a foaming roaring flood, which was as impassable as the Niagara. Looking towards the mountains perhaps ten or fifteen miles distant, I noticed for the first time the black speck of the cloudburst, which happened to be at the headwaters of this arroyo and no other. In a few hours I was able to cross, and on my return found some boulders to approach three feet in diameter. And this was ten to fifteen miles distant from the mountains! On the west slope of the Santa Rita mountains (east of Tucson) there is a ridge of rocks that was piled there by a torrent which later took a different course. These large boulders have remained invincible against the subsequent attacks of the water. This deposit has been mistaken for the moraine of an old glacier. . . . . The rate at which the mountains are torn down and the outwash deposits are built up, is rapid indeed when compared with the slower processes of ordinary erosion. As an example of this rate I shall mention the fact that the bottom layer of the Tucson outwash deposit, south of the Santa Catalina mountains, contains fragments of porphyries and lavas which do not appear in place on the south side of the range. The conclusion is evident that this layer represents a portion of the mountains entirely washed away. . . . . Sometimes great boulders are found at some distance from the mountains. I recall one case where, between a great boulder and the parent mass from which it had been detached, there was a short ridge or knoll fifty feet high. I was asked how the boulder could have traveled up over the hill to its present position without the aid of ice. I answered 'the surrounding country has been washed away and the hill left as a remnant, since the boulder rolled down from above.'"

Stratification.—The stratification in outwash deposits is especially developed. The alternate floods, of varying volume, now carry mud and now boulders, both depositing. Also the wind action described sorts out a protective layer of larger pebbles. The crusts develop a more or less stratified form, especially where the surface is level. This is, however, modified by a dome structure, due to the drying-out of the slightly elevated portion, causing a capillary flow in that direction, and accentuated by a slight erosion of the hollows.

Playa deposits.—The deposits of the playas vary considerably especially as they are formed (1) under a water sheet of moderate depth; (2) in a thin sheet as an evaporating mud surface; (3) as a flood-sheet deposit from a strong flow from above; and (4) these are all modified by wind erosion during periods of aridity. The strata deposited under lacustrine conditions need not be considered here, as the details of such deposition have been under geological observation for many years. An excellent summary of the details is found in Barrell's articles, cited above. Summarizing some of the points of especial import, the following are noted: (1) The strands and terraces of inland water sheets comprise some of the first of the climatic criteria discovered by geology; (2) coarse material is distributed in belts, parallel to the strands, and found only in their vicinity; (3) the deeper muds are largely wind-borne, and therefore of even fineness; (4) lack of subaerial markings of all kinds, within the body of the deposit, as well as of oxidation, are the chief features separating lacustrine from playa and subaerial delta deposits; (5) thick beds of pure sorted mica, floated out into deep water (observed in the Painted Canyon series, Mecca, California), indicate deep-water deposition under arid conditions.

On account of the lack of dissection of the playas visited, less data have been gathered on this subject than on the others.[1] Some of the characteristics have been inferred from observations on playas in the making.

Chemical deposits of the playas.—The chemical deposits of the playas are the more soluble salts, while that of the lower portion of the surrounding bajada is largely carbonate of lime.

Playa mud. Subaerial characteristics.—The well-known markings

[1] For characteristics discovered by Huntington in Turkestan, see *op. cit.*, p. 286.

due to the drying of a mud sheet show extreme development here. Wind, sand, and salt often comprise the filling of the mud cracks. *Mud crack tubes.* At the margin of the Salton Sea the drying-out of irregular mudcracks develops a surface crust of salt, arching over the crack. When well developed these become perfect tubes, and simulate the salt crusts deposited around small roots, or even fossil tubes of worm burrows. *Shallow channels caused by wind erosion* were excellently developed on the Salton beaches, and might find preservation in fossil playa deposits. Where the playa develops alternate extended and lacustrine conditions, restricted with well-developed beaches, dune formations, and blown-sand deposits, with plunging and truncated structure, invade and cover the playa muds. Special development of dune and standing-water action was noted in the area of the Crescentic Dunes, Carrizo Sands, Salton Basin, which explains some irregular structures showing fragments and lenses of wind sand in shale, noted especially in the Painted Canyon series, Mecca, and deserves, perhaps, at least a passing notice. Between the individual dunes, the ground is strewn with rock fragments, composed largely of pieces of strongly cemented dune sand, and protruding above the surface is a most irregular wind-sand formation, also cemented. Its irregular truncations and bevelments showed plainly that it was built up of truncated bottom layers of dunes that had passed over, leaving behind their bottom layers, captured by the salt seepage water, and later cemented by limonite, the whole formation showing the extreme conditions under which it was formed.[1]

Animal remains in playas.—Judging from the large number of bogged cattle that perish in the Arizona "cienegas" (fresh-water mud flats) during periods of drought, the same ought to be expected in older playas. Salt water would not attract the animals. The wind-rows of decaying fish that occur after flood intervals, in the Laguna Maquata, described and explained in the following quotation, are suggestive in connection with the development of petroleum, in strata deposited in arid regions suffering from periodic invasion by a strong river or the sea.

This low ridge of dead fish was seen to extend for about 15 miles and may have been double that length. A similar observation was made by Orcutt in

[1] Tolman, *loc. cit.*

1890, who found that the remains at that time were of mullet. From other sources it seems fairly probable that nearly every flood brings with it shoals of fish which find their way into the laguna. The shallow sheet coming in over the plain to the southward must furnish abundant food: but as the water rises in temperature and increases in concentration, it seems quite probable that a point is reached at which the water becomes poisonous to all of the finny inhabitants. Furthermore, this condition ensues at once and with sweeping effect, for the dead fish go ashore during so brief a period that no marked change of level has taken place; and as evaporation may be as great as half an inch a day, and scarcely ever is less than a quarter, the disaster must take place within a week or two.[1]

Plant remains.—There is a decided dearth of fossil remains on both bajada and playa deposits. In regard to the former this is to be expected, due to complete oxidation and lack of exploration. The playa deposits, especially the fresh-water playas, and the cienegas of the semi-bolsons would be expected to contain more in spite of subaerial exposure, for wood decay is extremely slow in arid regions, and the dense clay ought to help preserve the more resistant portions of the plants, such as the sahuaro ribs and such hard woods as mesquite. The prompt decay of the mesquite wood which was immersed under the expanded Salton Sea, and now exposed, suggests that even a small amount of salt dissolved hastens decay, for the Salton water contained (June, 1907, about 2½ years after the first break of the river into the basin only) about four times as much salt as the Colorado River at low water, and even now it is possible to drink the water under stress of necessity.[2] An interesting problem demands solution as to whether or not the Tertiary deserts were more deficient in plant covering than those of today.

Erosion of the dried playa.—This is entirely by wind action. The smaller the playa the more likelihood of desert pavements, on account of the larger proportion of pebbles contributed by the floods from above. Such fossil wind-erosion surfaces have been noted in deposits examined.

Relative importance of lake and outwash deposits.—A brief reconnaissance in the Salton Basin gave a good chance to compare the relative importance of the lake deposits, and those laid down in the bajadas. This basin has suffered many invasions by the river water,

[1] MacDougal, "The Desert Basins of the Colorado River," cited above, pp. 16, 17.

[2] For analyses, see MacDougal, *op. cit.*, p. 3.

each time forming a "sea." Many of these seas were sufficiently long-lived to develop excellent strand phenomena, and yet the basin, over which these advances and stays of the water took place, shows a most insignificant proportion of lake deposits compared with the detrital outwash from the mountains. It is little wonder that the early explorers, attributing all the depositional work to stan ing water, formed a very erroneous idea of the relative importance of lake deposition, and extended the sphere of its action far beyond that warranted by facts.

EFFECT OF CLIMATE ON THE EROSION OF THE BAJADAS

Turning again from facts to theory, let us investigate the effect of climatic variation on the erosion of the upper margin of the bajada. Space forbids a discussion of all the possible variations of climate on desert erosion, and moreover the profit resulting from such a theoretical discussion is very problematical. Even the limited investigation presented is more for the purpose of showing how

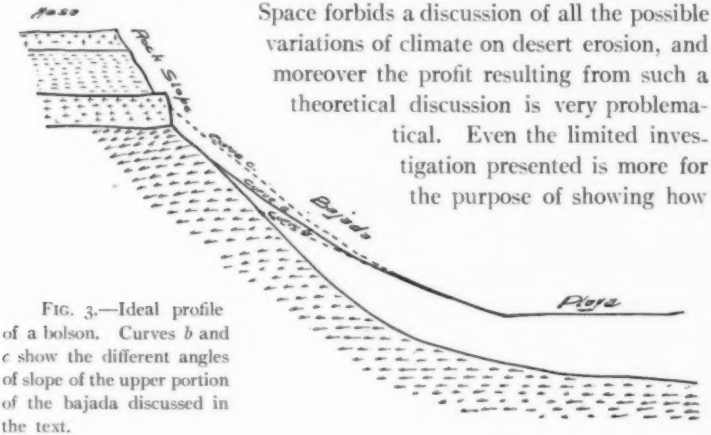

FIG. 3.—Ideal profile of a bolson. Curves *b* and *c* show the different angles of slope of the upper portion of the bajada discussed in the text.

complicated are the relations obtaining, and to emphasize the quotation which appears at the beginning of this article, rather than to develop working criteria.

Assuming that a playa is unaffected by earth movements that might displace it relatively to the surrounding bajadas, or by erosional attack of through drainage discharging to a lower level, a gullying from top to bottom would hardly be expected, and a minor incision especially of the upper portion would be more common. The initial slope is profiled by curve *a*, Fig. 3. Curve *b* shows the equilibrium

line with a lower angle of slope, a state of affairs that will result in the gullying of the bajada, while curve *c* indicates a condition that would result in rapid deposition. That such an erosion of the upper edge takes place irrespective of the conditions at the foot of the slope, is indicated by the fact that there are gullies which develop in the upper slope, but fade out before the bottom of the outwash is reached. Furthermore, an important criterion is discovered at this point. Should the bajada be gullied sharply from top to bottom, the cause may well lie in some change affecting the level of the playa, or the outwash drainage of the semi-bolson. North of Tuscon, in the Santa Catalina Mountains, there are remnants of an older and much higher bajada, than the well-developed lower and gullied slope. Preliminary studies suggested that this erosion might be connected with climatic change, but later it became evident that this was directly connected with the drainage developing at the foot of the slope.

Theoretical analysis, then, teaches us to look for variations of climate written in the upper slopes of the bajadas. The following is a list of those that ought to be most easily recognized:

Change in daily temperature difference variable, other factors remaining constant.

Change in torrential concentration variable, other factors remaining constant.

Change in plant covering variable, other factors remaining constant.

More effective still would be the immediate result of a decided swing, say from an effective daily temperature difference, to a marked torrential concentration, or the destruction of a heavy plant covering by aridity and a torrential concentration. Such possible factors were considered in attempting to explain the formation of the decided gullies that issue from the larger canyons of the Santa Catalina Mountains, and have incised the recent bajada,[1] but on close consideration it seemed more probable that these could best be explained by the fact that they drain a large area back in the mountains. The higher watershed receives more of the non-torrential winter rains, while the lower lands receive a larger proportion of their precipitation in the summer months and of a markedly torrential variety. The winter streams maintain a constant flow for several months, and are

[1] See the Topographic Map, Tucson Quadrangle, Ariz., U. S. G. S.

underloaded, and therefore slowly cutting. This erosion would be increased merely by increasing the proportion of winter precipitation to the whole.

Some idea of the delicate balance between climate and geological processes is gathered, when one considers that a slight shifting of the precipitation from the summer to the winter seasons produces a marked effect in erosion. Furthermore, differences in rock structure are more reliable as records of past climate than erosional features, so full of double meaning. Further investigation into possible criteria of climate change will not be undertaken here, although all the criteria suggested by studies so far have not been exhausted. If I have suggested some of the possibilities of the final results of this study, some of the working methods to be applied, some of the points that call most urgently for investigation, and some of the results that may finally be expected, the purpose of this contribution will have been fully accomplished.

THE WAVERLY FORMATIONS OF EAST-CENTRAL KENTUCKY[1]

WILLIAM CLIFFORD MORSE, Columbus, Ohio
AND
AUGUST F. FOERSTE, Dayton, Ohio

During a part of the summer just closed, the authors of this paper were engaged in working out the sub-Carboniferous stratigraphy of East-Central Kentucky for the state survey. The area covered extends from the Ohio River at Vanceburg southwestward seventy miles to the Kentucky River at Irvine. The results obtained, especially in the lower Waverly, are of sufficient interest, it is thought, to warrant publication.

The term Waverly was first applied to a series of rocks in Ohio. Under it are now included all of the rocks from the top of the Ohio shale to the base of the sub-Carboniferous limestone. In central Ohio the series has been divided into six formations, based upon their lithological characters. These formation names will be used, as far as possible, in the Kentucky field. They are, in descending order:

6. Logan formation.
5. Black Hand formation.
4. Cuyahoga formation.
3. Sunbury shale.
2. Berea grit.
1. Bedford formation.[2]

In the southern part of Ohio, however, the conglomerate phase of the Black Hand is not developed as it is in the central part. This makes the division of the upper Waverly into the Black Hand and

[1] Published by permission of Professor Charles J. Norwood, director of the Kentucky Geological Survey. Presented at the eighteenth meeting of the Ohio Academy of Science, Granville, November 28, 1908.

[2] C. S. Prosser, "The Classification of the Waverly Series of Central Ohio," *Jour. Geol.*, Vol. IX, pp. 214, 215, 1901. That the line of division between the Carboniferous and Devonian systems is still in doubt may be seen by referring to Professor Prosser's paper, "Revised Nomenclature of the Ohio Geological Formations," *Geol. Surv. Ohio, Bull. 7*, pp. 2, 17–21, 1905.

Logan practically impossible since the rocks, beginning with the upper Cuyahoga, are lithologically very similar. This is true also of the Kentucky field.

The lower formations, the Bedford, Berea, and Sunbury, and also the lower part of the Cuyahoga, on the contrary, are quite constant in this part of the state. They have been traced as far south as the Ohio River. Professor Prosser in the preparation of his paper on "The Sunbury Shale of Ohio" pushed the line just across the river and made a section at Vanceburg, Ky.[1]

Shortly after leaving the Ohio River, however, the Bedford and Berea rapidly thin out, allowing the Sunbury shale to rest almost directly upon the Ohio shale. The sandstones of these lower formations also disappear and are replaced by shales. There is also a marked westward thinning.

The discovery of these facts has contributed materially to the correct determination of the Waverly formations of eastern Kentucky. The presentation of these data together with their bearing upon the stratigraphy will form the chief part of this paper. This, probably, can best be accomplished by giving in order a few sections which clearly show the changes.

At the southeastern end of Vanceburg is a high hill known as Alum Rock. Along a path ascending this hill the rocks are nicely exposed from the Ohio shale to the lower part of the Cuyahoga. Since this section is one of the most typical of the lower Waverly in Kentucky, it will be given somewhat in detail, although it has already been published.[2]

SECTION OF ALUM ROCK, VANCEBURG

	Feet	Inches	Feet
5. *Cuyahoga formation*..... Interval covered except a thick layer of argillaceous sandstone at the top. The sandstone contains *Taonurus*. Small phosphatic nodules are found in the basal part of the interval.			39
4. *Sunbury shale*, total thickness..... Black, fissile, carbonaceous shales, which cannot be distinguished, lithologically, from the Ohio shale.			15½

[1] *Jour. Geol.*, Vol. X, pp. 292, 293, 1902.

[2] *Loc. cit.*

3.	*Berea grit*, total thickness			22¼
	Thick layer of gray sandstone	2	6	
	Heavy layer of rather coarse-grained gray sandstone, the upper surface excellently ripple-marked	3		
	Medium to thick-bedded rather coarse-grained gray sandstones, beautifully ripple-marked	15		
	Arenaceous shales	1		
	Layer of fairly coarse-grained gray sandstone		9	
2.	*Bedford formation*, total thickness			95⅝
	Blue arenaceous shales and shaly sandstones. Lower part slightly covered	35		
	Arenaceous shales with thin sandstone partings	7		
	Layer of thick-bedded gray sandstone	1	8	
	Arenaceous shales with two layers of sandstone	6	9	
	Heavy layer of gray sandstone, with lower surface contorted	2	4	
	Arenaceous shales with two layers of gray sandstone	6	6	
	Layer of thick-bedded buff sandstone	1	9	
	Medium-bedded gray sandstones with shaly partings	2	10	
	Arenaceous pink shales with sandstone partings	2	6	
	Covered interval	5		
	Layer of thick-bedded, buff sandstone	2		
	Practically covered interval with some argillaceous shales.	22	6	
1.	*Ohio shale*			242
	Black fissile, carbonaceous shales. About ten feet from the top, one or two linguloid shells occur. Near the central part the shales become softer and lighter in color and resemble a similar zone in the Ohio at Columbus, (Ohio). The interval (242′) is mostly exposed and extends to the level of the Chesapeake and Ohio Railroad. At "Slate Point," however, the top and bottom contacts are shown and the total thickness is 301¼ feet.			

The most striking feature of this section is the development of sandstones within the Bedford formation, which usually consists of shales alone. This feature recalls a similar development in northern Ohio. Along Euclid Creek, east of Cleveland, sandstones occur in quite regular layers at about the same horizon, and are extensively quarried. They are known to the trade as the Euclid stone and the division has been appropriately named the "Euclid lentil" by Professor Prosser.[1]

[1] Used in a manuscript not yet published.

Alum Rock hill extends only a short distance, 39 feet, above the Sunbury shale and this interval is practically covered except at the top where a massive layer of sandstone is exposed. Higher strata are found, however, in an adjacent hill known as "Slate Point." Near the summit the lower Cuyahoga is quite well exposed along the road which ascends the hill. It consist of even-bedded argillaceous sandstones or freestones with shaly partings and is the typical Buena Vista member.[1]

On the Petersville Road some three miles south of Vanceburg is a long hill known as the Vanceburg hill. After this is crossed, the Sunbury shale is found at its base, and below, 19½ feet of the top of the Berea grit. Instead of being a massive sandstone, as at Alum Rock, the most of this interval is composed of arenaceous shales and shaly sandstones, only 2½ feet reaching the proportions of a thin-bedded sandstone. The upper two feet have been considerably disturbed while the last layer varying from 0 to 9 inches is badly contorted. There was no question as to this identification, however, as the sandstones were excellently ripple-marked and were directly overlain by the complete Sunbury.

Such marked lithological changes in so short a distance are very striking and should cause subsequent study to be performed more critically. They also prepare us for, or cause us to anticipate, other changes.

At various places along the next six or eight miles of this same road, slight exposures show that the area has been somewhat disturbed. This is mostly in the form of folds and affects the top of the Ohio shale and the Bedford and Berea. In one place the movement was sufficient to cause a fault but the exposure was not large enough to show the amount of displacement.

Thirteen miles south of Vanceburg, at the home of J. E. Kegley, the Petersville Road crosses a small run called Elk Lick. At the road side south of this stream is a steep hill, upon the side of which the Ohio, Berea, and Sunbury are exposed. While the out-crops are not all that could be desired, yet they show that the Bedford and

[1] For the revival and present usage of the term "Buena Vista" and another, "City ledge," to be used later, the reader is referred to pages 341 and 342 of Professor Prosser's paper on "The Waverly Formations of Central Ohio," *Am. Geol.*, Vol. XXXIV, 1904.

Berea have thinned from 118 feet to a total not exceeding 75 feet in this distance.

ELK LICK CREEK SECTION

	Feet	Inches	Feet
4. *Sunbury shale.* Pieces of black, fissile, carbonaceous shale directly above the sandstone layers.			
3. *Berea grit* 2. *Bedford formation* Medium-bedded sandstones, ripple-marked on the upper surfaces. Unquestionably Berea	7	6	75
Covered interval, which probably contains the contact of the Bedford and Berea	67	6	
1. *Ohio shale* Black, fissile, carbonaceous shales, which extend down to the level of the highway at the spring.			30

In the second gully west of the schoolhouse in Petersville, the strata are exposed more or less completely from the Ohio shale to the lower Cuyahoga formation. By combining the exposures of both branches of this gully, an almost continuous section is had from the top of the Ohio to the top of the Sunbury. This is the key section to the lower Waverly problem. The Bedford and Berea cannot have a total thickness of over 46½ feet, showing a thinning of over 70 feet in 18 miles or nearly 30 feet in 5 miles. The sandstones, too, have also practically disappeared, leaving only the shales behind. Whether these belong to the Bedford alone or to the Bedford and Berea is still an open question as both formations contain sandstones at Vanceburg. If a section of about normal Berea, underlain by shales only, were obtainable somewhere in the vicinity of Elk Lick, then these 46½ feet could be referred to the Bedford. However, such a section has not been and probably never will be found. The shales probably belong in part to the Bedford and in part to the Berea. If this be true they cannot be separated into the two formations from here southward and for the present, at least, they will be designated together under the inclusive term Bedford-Berea.

PETERSVILLE SECTION

	Feet	Inches	Feet
4. *Cuyahoga formation* Medium to heavy-bedded, gray, argillaceous sandstones with shaly partings	14		55½
Covered interval	41	6	

3. *Sunbury shale*, total thickness			12½
Black, fissile, carbonaceous shales.			
2. *Bedford-Berea*, total thickness			46 1⁵/₂
Covered, except some arenaceous and calcareous shales, which are probably ripple-marked	14		
Bluish to buff arenaceous shales with an occasional parting, ripple-marked	17	6	
Blue, argillaceous to arenaceous shales with an occasional calcareous or arenaceous parting	7		
Thin layer of sandstone		5	
Blue, argillaceous shales with a little black, carbonaceous shale at the base	4	3	
Covered interval	2	6	
Soft, argillaceous shales mixed with some black shales		9	
1. *Ohio shale*			85
Black, carbonaceous shales, slightly covered	85		
Covered, to the water level of Kinniconick Creek at the church	10		

Near Fox Springs, Fleming County, an exposure shows a probable thickness of 32½ feet for the Bedford-Berea. While the horizon continues to thin to the southward, the rate of decline is much more gradual than it has been in the area just discussed, and for this reason sections will now be given at longer intervals only.

In the highway leading up the hill at Rockville Station, Rowan County, is an excellent exposure from the Ohio shale to the lower Cuyahoga. The Bedford-Berea is only 18½ feet thick, but probably the greatest value of the section is its aid in determining the true horizon of the sandstones quarried in this vicinity. These have been referred to the Berea grit by Hoeing,[1] but a glance at the following section will show that they belong to the Buena Vista member of the Cuyahoga formation. The Buena Vista sandstones with shaly partings are typically developed but the interval is only 37 feet as compared with 60 feet for the same member along the Ohio River west of Portsmouth, Ohio.

SECTION AT ROCKVILLE STATION

	Feet	Inches	Feet
Soil to the level of the peneplain	15		
4. *Cuyahoga formation*			90
Soft, blue, argillaceous shales with an occasional ferrugi-			

[1] *Kentucky Geol. Surv., Bull. I*, p. 49.

	Feet	Inches	Feet
nous parting. The lower two feet covered, but probably shales	35		
Soft, blue, argillaceous shales alternating with thin to medium-bedded argillaceous sandstones, the shales predominating	18		
Top of the Buena Vista member and also the top of the stone quarried. Even-bedded argillaceous sandstones, "freestones," with thin partings of blue argillaceous shales. The sandstones contain *Taonurus*. The layers are mostly medium-bedded, that is of proper thickness for commercial use. Their size together with the shaly partings render them easily quarried. They are quite extensively worked and make a beautiful and excellent stone	25	6	
Soft, blue, argillaceous shales with three or four shaly sandstone partings, which contain *Taonurus*	4	6	
Soft, blue argillaceous shales	7		
3. *Sunbury shale*, total thickness			16¼
Black, fissile, carbonaceous shale.			
2. *Bedford-Berea*, total thickness			18½
Soft, blue, argillaceous and finely arenaceous shales, and fine-grained shaly sandstone. The lower two feet have one or two thin layers of black, fissile shale.			
1. *Ohio shale*			20¾
Black, fissile, carbonaceous shales	2		
Covered to the level of the Chesapeake & Ohio Railway Exposures in a nearby gully and the main stream show, however, that all of this interval is Ohio shale	18	9	

Quite a variation in the thickness of the Bedford-Berea occurs along an east-and-west line at Olympian Springs, Bath County. This variation will be given here to prepare us for the remarkable thinning farther southward. Two sections were made within a radius of a mile of the Springs. In the eastern of these the horizon measured 12½ feet, in the western 5¾ feet, while on the opposite side of the hill from the latter and a half mile farther west, the thickness was only 2 inches. The Sunbury on the contrary was quite regular, measuring 12⅓, 12¾, and 12 feet for the respective sections.

From Olympian Springs southwestward, at least on the western border of the Cuyahoga outcrops, the sandstone layers of the Buena Vista member begin to gradually disappear. By the time Jefferson-

ville, Montgomery County, is reached, only a single layer remains. It occupies the position of the lowest, but whether or not it is one and the same layer or different layers at the various exposures to the southward cannot be determined. From its position in the following section, which was taken one mile east of town, it will be seen to occupy the position of the "City ledge."

SECTION AT SLATE CREEK BRIDGE, JEFFERSONVILLE

	Feet	Inches	Feet
4. *Cuyahoga formation*			5½
Layer of massive, argillaceous sandstone with *Taonurus* abundant. In this vicinity exposures are sufficient to show seventeen or eighteen feet of argillaceous shales above this layer	2	10	
Soft argillaceous shales	2	3	
3. *Sunbury shale*, total thickness			11
Black, fissile, carbonaceous shales.			
2. *Bedford-Berea*, total thickness			4⅛
Bluish to dark, slightly ferruginous, argillaceous shales.			
1. *Ohio shale*			31½
Black, fissile, carbonaceous shale to the base of the exposure	31	6	
Black shales extend to the level of Slate Creek at the bridge, but these were not measured.			

Still farther south the lower layer finally disappears. In place of the Buena Vista sandstones, soft, argillaceous shales occur in the lower Cuyahoga. To these clayey shales, August F. Foerste applied the term "Linietta clay," provisionally, before their identity with the New Providence shale of southern Indiana was ascertained.[1] The New Providence shale with the overlying Riverside sandstone, it will be recalled, make up the Knobstone formation of Indiana.

About Indian Fields in Clark County, the Ohio shale extends to near the top of the hills. One mile east of the station, along a highway passing within a quarter of a mile of Oil Springs, the following section was taken. The chief interest in this one is, that while the Bedford-Berea is only two inches in thickness, the shales are fossiliferous. More will be said about these fossils after the Irvine section has been given.

[1] *Kentucky Geol. Surv., Bull. VII*, p. 14.

SECTION AT INDIAN FIELDS

	Feet	Inches	Feet
3. *Sunbury shale*.....			9½
Black fissile, carbonaceous shales.			
2. *Bedford-Berea*, total thickness.....			½
Fossiliferous, argillaceous, and calcareous shales.			
1. *Ohio shale*.			
Black, fissile, carbonaceous shale extending down the hill for a long distance but not measured.			

An instructive section is seen one mile northwest of Stanton, Powell County, in a lane leading up to the residence of Lewis Foulkner.

SECTION AT STANTON

	Feet	Inches	Feet
4. *Cuyahoga formation*.....			41
Soft, blue, argillaceous shale not measured.			
Layer of buff, fine-grained, calcareous sandstone, which weathers into large flat nodules.....	1	3	
Soft, blue, argillaceous shale.....	3		
3. *Sunbury shale*, total thickness.....			6½
Black, fissile, carbonaceous shale.			
2. *Bedford-Berea*.....			7/12
Bluish, argillaceous, and calcareous shales.			
1. *Ohio shale*.....			16½
Black, fissile, carbonaceous shale.....	16	6	
Covered to the highway.....	19	9	

The final section is from Irvine, Estill County. Here the Bedford-Berea is 1 foot, 6 inches in thickness and fossiliferous, while the Sunbury is only 3 feet. This very gradual decrease in the Sunbury should be noted although it is much less marked than the thinning of the Bedford-Berea.

SECTION OF MINERVA MOUNTAIN, IRVINE

	Feet	Inches	Feet
6. *Sub-Carboniferous limestone*.....			1
Yellowish, sandy-like limestone, lying at the extreme top of the hill.			
5. *Upper Waverly series*, not divided.....			344
Covered interval.....	60	6	
Thin bedded, buff, argillaceous sandstones, which weather to thin shaly pieces, *Taonurus*.....	17		
Layers of massive, buff, argillaceous sandstone, *Taonurus* abundant.....	24		

Buff, argillaceous sandstones, weathering to shales. *Taonurus*	17		
Covered interval	225	6	
4. *Cuyahoga formation*, top not determined			144
Brownish, ferruginous, and calcareous, nodular layer of sandstone		6	
Indurated, bluish to pinkish, argillaceous shales with ferruginous, nodular layers	69	6	
Soft, bluish, argillaceous shale with ferruginous, nodular layers, slightly covered (top of Linietta clay)	63	6	
Layer of brownish, argillaceous sandstone, which breaks up into shaly layers	2		
Soft, bluish to pinkish, argillaceous shales with small phosphatic nodules	8	6	
3. *Sunbury shale*, total thickness			3
Black, fissile, carbonaceous shales.			
2. *Bedford-Berea*, total thickness			1½
Argillaceous shales with phosphatic nodules		2	
Black, fissile, carbonaceous shales		3	
Dark, argillaceous shales, with some carbonaceous material		6	
Gray, calcareous, and argillaceous shales, slightly fossiliferous		2	
Yellowish, calcareous, and argillaceous shales, the upper part very fossiliferous		5	
1. *Ohio shale*			94½
Black, fissile, carbonaceous shales, with an occasional softer argillaceous layer. Practically all exposed to the highway.			

The thinning-out of these formations can probably be more clearly shown graphically. The sections that have just been described are grouped in the two accompanying figures, and follow each other consecutively.

Several of the fossils collected at Irvine and also at Indian Fields when compared with those from the base of the Bedford at Columbus, Ohio, prove to be the same species. Of these *Macrodon hamiltoniae* is the most abundant one common to both fields. This paleontological confirmation of the conclusion reached by a lithological study is surely gratifying.

It may be argued from this that the thin argillaceous horizon should be referred to the base of the Bedford rather than to the Bedford-

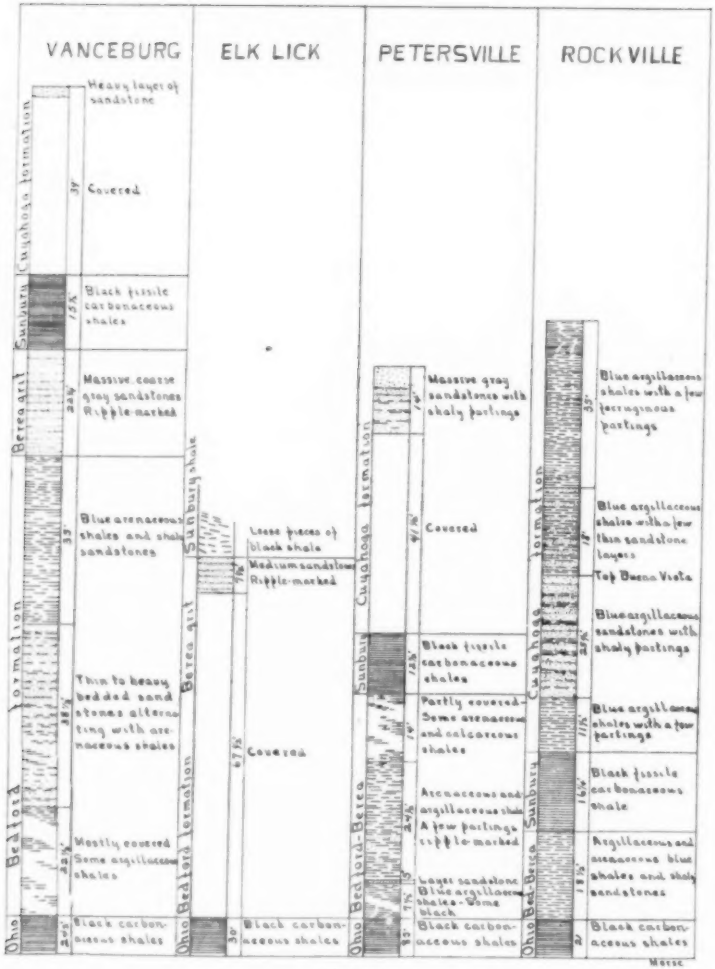
VANCEBURG
ELK LICK
PETERSVILLE
ROCKVILLE
Cuyahoga formation
Sunbury
Berea grit
Bedford formation
Ohio
Heavy layer of sandstone
Covered
Black fissile carbonaceous shales
Massive coarse gray sandstones Ripple-marked
Blue arenaceous shales and shaly sandstones
Thin to heavy bedded sandstones alternating with arenaceous shales
Mostly covered Some argillaceous shales
Black carbonaceous shales
Sunbury shale
Loose pieces of black shale
Medium sandstone Ripple-marked
Covered
Black carbonaceous shales
Massive gray sandstones with shaly partings
Covered
Black fissile carbonaceous shales
Partly covered Some arenaceous and calcareous shales
Arenaceous and argillaceous shale A few partings ripple-marked
Layer sandstone Blue argillaceous shales - Some black
Black carbonaceous shales
Blue argillaceous shales with a few ferruginous partings
Blue argillaceous shales with a few thin sandstone layers
Top Buena Vista
Blue argillaceous sandstones with shaly partings
Blue argillaceous shales with a few partings
Black fissile carbonaceous shale
Argillaceous and arenaceous blue shales and shaly sandstones
Black carbonaceous shales
Morse

FIG. 1

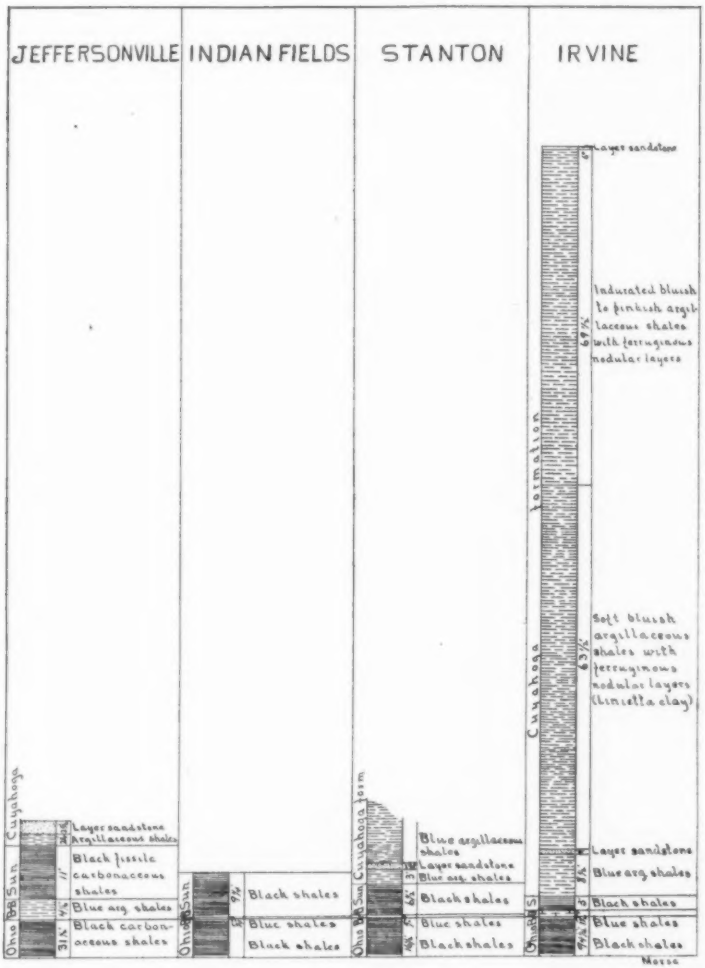
JEFFERSONVILLE
INDIAN FIELDS
STANTON
IRVINE
Cuyahoga
Layer sandstone
Argillaceous shales
Black fissile carbonaceous shales
Blue arg shales
Black carbonaceous shales
Ohio Sh.
Sun.
Black shales
Blue shales
Black shales
Cuyahoga form.
Blue argillaceous shales
Layer sandstone
Blue arg shales
Black shales
Blue shales
Black shales
Layer sandstone
Indurated bluish to pinkish argillaceous shales with ferruginous nodular layers
Soft bluish argillaceous shales with ferruginous nodular layers (limestone clay)
Layer sandstone
Blue arg shales
Black shales
Blue shales
Black shales
Morse

FIG. 2

Berea. This is a strong argument, yet from facts set forth above it seems advisable to refer the rapidly decreasing horizon to the Bedford-Berea.

In this connection, it might be well to give the conclusions reached by Professor Williams in his paleontological study of the black shales. He states that an

> examination of the sections at Irvine, Kentucky, the other side of the Cumberland channel revealed the fact that there the black shales were thinner but held on in their purity, well up into Carboniferous time. The intercalations consist of calcareous and ferruginous, concretionary sheets, and carry undoubted Carboniferous fossils and occur in the sections before the black shale loses its characteristic expression.[1]

These black shales have been correlated with the Ohio black shale in the various geological reports of the state. The geologists of the National Survey, approaching the field from the south, have, on the other hand, designated them as the Chattanooga shale.[2] Both have referred them, in their entirety, to the Devonian system. That they belong to both the Devonian and Carboniferous systems has, it is thought, been clearly demonstrated.

Of the London and Richmond Folios of the U. S. Geological Survey, the latter adjoins the Irvine field. In these Campbell has designated the clay shales and argillaceous sandstones, above the Black shale, as the Waverly formation. It is permissible, according to the rules of that survey, to reduce a series to the rank of a formation, but, as applied here, Waverly covers not more than the upper half of that division. The lower half, Bedford, Berea, and Sunbury, has just been shown to be included within the limits of the Chattanooga (Ohio) shale.

It is interesting to note that Professor Grabau anticipated this limitation. Referring to the London Folio, he states that:

> The shale above the Black (Ohio) shale is referred to the Waverly, of which it probably constitutes the upper portion only. As at Irvine, the transition from the Black shale to the overlying beds is probably a gradual one.[3]

This conclusion seems to have been reached deductively, from a

[1] *Am. Jour. Sci.*, 4th series, Vol. III, p. 398.

[2] Estillville, London and Richmond Folios, U. S. Geol. Surv.

[3] *Bull. Geol. Soc. Am.*, Vol. XVII, pp. 609, 610.

study of Professor Williams' paper which he quotes and to which reference was made above.

To summarize, then, it may be stated that: The Bedford and Berea formations thin rapidly southwestward from the Ohio River and this horizon, even after it has been reduced to a thickness of only a few inches, can be traced to near the crossing of the Cincinnati geanticline by the Waverly series.

The Sunbury shale, on the contrary, suffers but little decline, at least until Indian Fields is reached.

The Ohio black shale of the Kentucky reports or the Chattanooga shale of U. S. reports, south of Petersville, is not of Devonian age alone but of Devonian and Carboniferous, that is, is composed of both the Ohio and Sunbury shales, and a thin zone representing the Bedford and Berea.

The sandstones, which are extensively quarried about Rockville Station belong to the Buena Vista member of the Cuyahoga formation rather than to the Berea grit.

The Buena Vista sandstones begin to disappear from Olympian Springs southwestward except a single layer which, if not always the same, at least occupied the position of the lowest and which persists as far south as Stanton if not to Irvine.

The Linietta clays belong to the lower part of the Cuyahoga formation.

The so-called Waverly of at least the Richmond Folio includes only the upper part of the Waverly, beginning with the base of the Cuyahoga.

NOTES ON THE POINT HOPE SPIT, ALASKA[1]

E. M. KINDLE

Point Hope is a spit of gravel and shingle which extends out into the Arctic Ocean from the northwestern coast of Alaska, about one hundred and twenty-five miles north of the Arctic Circle. It marks the most westerly point reached by the continental shore line north of Kotzebue Sound. After Cape Prince of Wales it is the westernmost point of the continent. (See Fig. 1.) Point Hope extends seaward from the delta of the Kukpuk River and represents the northwestern extension of the barrier beach which curves southeastward to the cliffs at Cape Thompson, a distance of about thirty-five miles. The spit and the delta deposits behind it together extend out a distance of about fifteen miles beyond the bed-rock area of the original shore line. Lagoons and barrier bars are a common feature of the northwestern coast of Alaska, but spits extending out into the sea are unusual and the Point Hope spit is unique in being the only spit along this coast line which projects any notable distance into the sea at right angles to the coast line. Point Barrow and the long bar forming Point Clarence Harbor are the only spits on the northwestern coast of Alaska which are comparable in size with the Point Hope spit. Neither of these, however, shows the finger-like projection from the coast line of Point Hope, each of them curving toward the eastward. The natives have named this rather striking physiographic feature "Tigara," from its fancied resemblance to the index finger of the hand, which the word signifies.

Abo t one and three-fourths miles from its western extremity the Point Hope spit is joined by a bar which is only about one hundred yards in width at the point of junction with the spit. This bar extends in a northeasterly direction nearly to the mainland and forms with the spit a V-shaped figure inside of which are the shallow waters of Marryat Inlet and the delta of the Kukpuk River.

It will be seen by reference to the map (Fig. 2) that the unconsolidated beds which lie to the west of the area of bed-rock outcrops in the neighborhood of the mouth of Kukpuk River cover a rather extensive area. They represent in large part delta deposits and in part fore-

[1] Published by permission of the Director of the U. S. Geological Survey.

land and beach deposits. We are here concerned only with the latter. The delta deposits are easily distinguished as a rule and usually consist of interstratified silts and sands overlaid by fine black sediments

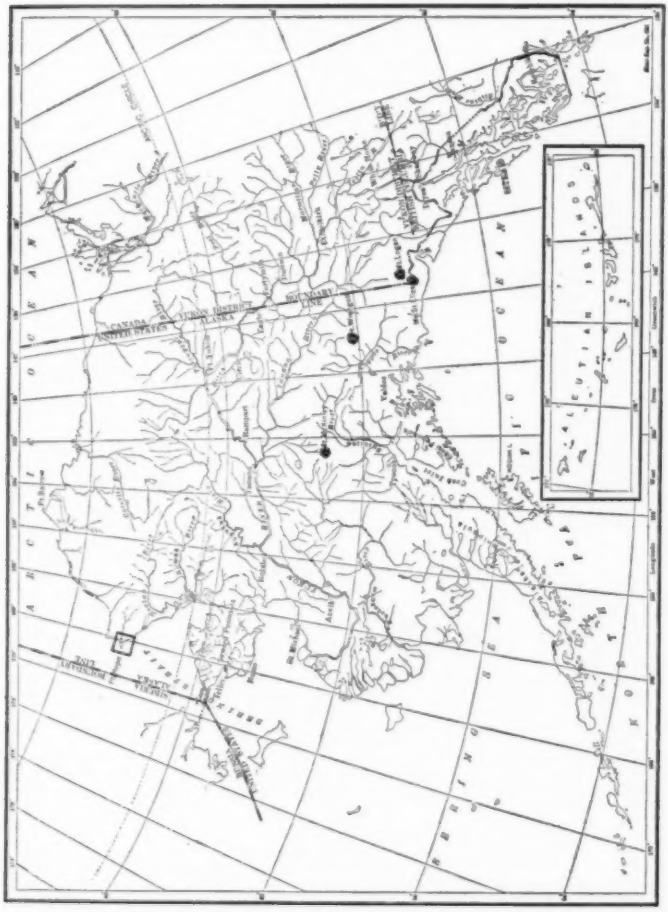

FIG. 1.—Outline map of Alaska, showing by rectangle the area of the Point Hope map.

which are often interbedded with peat-like accumulations of marsh grass turf.[1]

[1] Mr. A. J. Collier gives a brief description of the delta deposits in a report on the Cape Lisburne coals, *Bull. U. S. G. S., No. 278*, p. 33, 1906.

A regularly concave shore line connects the base of the spit with the cliffs of Cape Thompson from which most of its materials are derived. A narrow gravel barrier beach, frequently only 100 or 200 feet in width, forms the coast line of this concave beach, a distance of about 25 miles. Behind this beach is a series of lagoonal fresh-water lakes which drain by filtration through the beach. The beach is

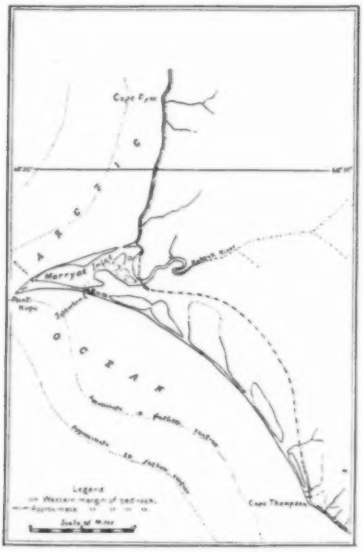

FIG. 2.—Reconnaissance map of Point Hope and adjacent coast line. By E. M. Kindle.

unbroken by streams entering the sea, except within the first mile to the west of Cape Thompson.

The south shore of the spit is generally steep, while the northwest shore is less abrupt. The point terminates abruptly in rather deep water, 13 fathoms being recorded a few ship's lengths from the tip of the point. Off the south shore the eight-fathom contour runs within a quarter of a mile of the shore toward the western end of the Point. On rounding the Point the soundings decrease rapidly to

five fathoms and a shoal with four fathoms at its southern end extends some three miles in a west-northwest directin from the Point.[1]

The materials composing the spit are much coarser than those of many spits. Much of it may be properly called shingle, while coarse gravel and a small proportion of sand comprise the remainder of the material. The coarser materials are composed of limestone and chert. From the point where the spit joins the delta deposits at Jabbertown to its western extremity, its length is about eight miles. The surface of the spit has an elevation ranging from thirteen to seventeen feet above the sea. Its greatest width is near the mission where it is about one mile from the north to the south side.[2] From this point it tapers gradually toward the east. It reaches its minimum width near its base where it is less than a quarter of a mile across.

An interesting feature in the make-up of the spit is a series of regular straight canal-like depressions trending nearly east and west and lying parallel with the south shore. The northwest shore line cuts these channels at an acute angle. The bottoms of the channels are depressed below the general surface of the spit from two to six feet. The shallower ones are entirely dry and would hardly be noticeable were it not for their distinct parallelism with the deeper ones. Water remains throughout the summer in two or three of the deeper ones, and it is from this source that the native village secures its water supply. In width these depressions will range perhaps between forty and one hundred feet, and the intervening spaces will average probably two hundred feet. The sides curve very gently into the surface of the interval separating them, which frequently is slightly convex. These canals all extend to the northwest beach, which cuts them off forming an acute angle with the north border of the depression. To the eastward most if not all of them can be recognized at least two miles from the western extremity of the point. Two of them are considerably deeper at this distance than farther west. Near

[1] Lieutenant D. H. Jarvis, "Coast Pilot Notes on the Fox Islands Passes, Unalaska Bay, Bering Sea and the Arctic Ocean as far as Pt. Barrow," *Bull. Coast and Geod. Survey, No. 40*, p. 56, 1900.

[2] As a basis for determining the amount of wave-cutting on the northwest shore of the spit by future observers, the distance from the north side of the mission observatory to the water line on the northwest beach was measured on a north and south (true) line and found to be 525 feet.

the base of the spit at Jabbertown most of these depressions have faded out. Observations on the bearing of each of these have shown that the four northernmost of the series differ from the others in direction several degrees and are parallel to the south shore of Marryat Inlet. The south shore of the inlet here bears about S. 73° E. Two of the first four canals south of it have the same bearing, while the other two bear respectively S. 74° and S. 75° E. The other canals to the south of these are nearly parallel with each other and with the south shore. Twelve of the latter have been recognized. The variation in the direction of these is within the limits of S. 83° E. and S. 90° E. Under the name of aggradation lines Dr. F. P. Gulliver describes what appear to be similar features in the Dars foreland in the Baltic Sea, Carraveral foreland, Florida, and other cusps.[1]

The writer's observations seem to establish two important facts relative to the present action of destructive and constructive agencies on the spit. The northwest shore is being cut away rather rapidly while the south shore is being built up. The ruins of an ancient Eskimo village, which is being undercut by the waves, afford indisputable proof of the encroachment of the sea on the northwest side. We have also the testimony of a missionary, Dr. John Driggs, who has resided for 18 years near the north shore of the point. He states that 185 feet would be a very conservative estimate of the amount of cutting which has occurred on the north shore during the period of his residence. He informed the writer that the cutting of the shore was accomplished almost entirely during the prevalence of heavy southwesterly or westerly storms. At such times the waves are driven along the beach and carry away its loose materials very rapidly. The writer was shown the door of the old mission chapel standing about sixteen feet above the sea and some two hundred and fifty feet from the beach which was smashed by wave action during a southwest storm of exceptional violence which occurred October 13, 1893. It appears that during this storm the sea was banked up on this coast until one to three feet of water covered nearly all the western portion of the spit.

The evidence that constructional work is in progress on the south side of the spit is based in part on the relative freshness of the gravels

[1] *Proc. Am. Acad. Arts and Sci.*, Vol. XXXIV, p. 180, 1899.

on the north and south sides and the comparative extent to which vegetation has secured a foothold on the two sides. A few varieties of grass, which constitute nearly the sole vegetation, extend everywhere along the north shore up to the limit of wave action. On the south side the gravel is fresh-looking and in many places is entirely barren of vegetation for two or three hundred yards from the shore.

It is interesting to note that the first white men to land on this point were impressed with the recent character of some of the deposits, comprising the spit. Mr. A. Collie, who was a member of the scientific staff of Captain Beechey's expedition to this coast in 1827, made the following observations concerning it:

> To the north of Cape Thompson the coast runs out by means of a low spit to the distance of perhaps 20 miles into the sea. The low point itself seemed to be acquiring almost a daily accession to the basaltic gravel of which the beach was in greater part formed.[1]

The location of the Point Hope spit is undoubtedly due in large measure to the combined influence of the Kukpuk River and a coastwise current which sets northward out of Kotzebue Sound, at from one to three miles an hour. This current appears to be continuous with the current which sets northward through Bering Strait during the summer months. The current through Bering Strait forks a short distance north of the Strait, one branch bearing northwesterly along the Siberian coast, and the other "going north through Kotzebue Sound and thence along the mainland by Cape Seppings, Point Hope, and Icy Cape to Point Barrow at which point it goes off to the unknown northeast."[2]

The drift of the ice-beset "Jeannette" seems to be conclusive evidence of the northwesterly current to the west of the Strait.

The current through Bering Strait may, of course, be greatly accelerated or retarded by the winds, but they do not seem to be ever able to entirely check it. Captain F. W. Beechey recorded that he found a current in Bering Strait running against a heavy gale "at the rate of upward of a mile an hour in a N. 41° W. direction."[3]

The influence of this current is manifested as far south as Teller

[1] *Zoölogy of Captain Beechey's Voyage*, London, Bohm, 1839, p. 172.

[2] Chas. H. Stockton, *Natl. Geog. Mag.*, Vol. II, 1891, p. 183.

[3] *Narrative of a Voyage to the Pacific and Bering Strait*, Part II, 1831, p. 546.

on Seward Peninsula and it is reported to reach even as far to the eastward as Point Barrow. McClintock found a current setting eastward to the east of Point Barrow with a rate of 18 miles per day.[1] The depth of water affected by this current seems to be but a few feet. The writer observed evidence of this while aboard a schooner anchored off Cape Krusenstern in Kotzebue Sound during a calm. The waters of the sound swarm with various species of medusa and other plankton. From the rail of the anchored schooner these could be seen at and near the surface passing the vessel with a current of one and one-half or two miles an hour. A few feet below the surface, however—perhaps 10 or 12 feet—could be seen the same fauna almost or quite stationary. The shallow character of this northerly current in these waters was noted as early as 1826 by the careful observations of Captain F. W. Beechey who states concerning this current that "at the depth of nine feet its velocity was evidently diminished and at three and five fathoms there was none."[2] Captain Beechey observed also that the water of this current was much fresher than the deeper waters.

The writer has had abundant opportunity to note the influence of this current on coast deposits in the course of a 200-mile journey in a small boat along the coast of Seward Peninsula and near Cape Thompson. Almost every stream between the lagoon west of Teller and Cape Prince of Wales is deflected to the right by a bar on entering the sea. The long narrow bar at the mouth of Kanauguk River is a typical example of these bars. In the case of small creeks the bar may be only three or four yards wide, but when present it invariably turns the stream abruptly to the right as it is about to enter the sea. The tendency of the northerly current to deflect streams to the right is illustrated in Kotzebue Sound, by the bar at the mouth of the Inmachuk River. This bar has a length of about a third of a mile and extends nearly across the mouth of the valley occupied by the Inmachuk, forcing the river to enter the sound at the extreme east side of the valley. A small creek at Cape Thompson which is deflected abruptly to the right by a narrow bar is the nearest example to Point Hope of the influence of this current.

[1] Capt. McClintock, *A Narrative of the Discovery of the Fate of Sir John Franklin and His Company*, p. 72, 1868.

[2] *Op. cit.*, p. 578.

The relative position of shoals and coastal headlands likewise indicates the influence of the northerly current. An extensive shoal extends northward from Cape Prince of Wales for many miles with comparatively deep water south of the cape. At Point Hope a detached shoal with four and one-half feet of water over it lies to the north of the Point with deep water south of the Point. Cape Lisburne likewise has an outlying shoal with five fathoms of water over it, but it lies wholly to the north of the cape. At Point Barrow there is also a shoal lying wholly to the north of the Point.[1]

The bars cited, however, differ from the Point Hope spit in running parallel with the shore. Like them the Point Hope spit appears to have deflected the stream to the north, but unlike them it extends out nearly at right angles to the coast line. The considerable volume of the discharge of the Kukpuk River has no doubt been an important factor in neutralizing the tendency of the coastal current to turn the spit to the north.

In this connection tidal influence may also be considered. The tide, although small in the Arctic Ocean, is not a negligible element in considering the development of shore-line features. The mean range of the tides recorded for the northwest coast of Alaska and the adjacent parts of Siberia ranges from .2 of a foot[2] to 2¼ feet.[3] The tide at Point Hope is probably considerably less than two feet, but it is sufficient to give at the ebb a current to the southwest off the northwest shore of Point Hope.[4] This tidal-ebb current from the northeast would neutralize the tendency of the coast current to turn the point of the spit northward and the collision of the two currents would lead to the shore waste which they carried being dropped so as to build the point in a westerly direction. The cliffs forming the coast line at Cape Thompson have a northwest-southeast trend for six miles or more, giving the coast current its initial northwesterly or seaward trend. North of the Kukpuk River for nearly thirty-five miles the coast line of cliffs trends nearly north and south. This contrast in the trend of the coast on the north and the south sides of the point

[1] U. S. Hydrographic Office, Chart of the Bering Sea and the Arctic Ocean.

[2] Harris, *Eighth Intern. Cong. of Geog.* p. 399, 1905.

[3] DeLong, *Voyage of the "Jeannette,"* p. 890, 1883.

[4] Capt. F. W. Beechey, *op. cit.*, p. 577.

probably gives rise to a slight backset or eddy current to the southwest on the north shore of Point Hope, which may be an element in giving the spit its cuspate form.

In addition to the familiar marine agents, waves, tides, and currents, which are involved in shaping the shore-line features of all coasts, we have on the Arctic coasts a fourth agency which at times acts with far greater power and rapidity than either of the above-named influences. This is the Arctic ice-pack. The shallow character of all the navigable portion of the Arctic Ocean, north of Bering Strait which seldom exceeds 30 fathoms, affords peculiarly favorable conditions for the excavating and plowing activities of the ice-pack when grounded and under pressure. The nature of the difference between ordinary sea ice and the ice of the ice-pack is indicated in the following extract from Captain Hooper's "Ice Notes":

> The greatest thickness attained by direct freezing is about eighteen feet, at which thickness the increase by freezing at the bottom does not exceed the waste at the top by evaporation, which goes on slowly but surely at all times. The maximum thickness by direct freezing is generally reached the third winter. It is seldom that more than nine feet forms during one winter. The extraordinary thickness attained by the pack is due to accumulations of these naturally formed layers as they are forced one over the other by pressure due to currents of air and water. On account of the difficulties of ascertaining the thickness of the ice by measurement, the most reliable way appears to be by noting the depth of water at which it touches the bottom. This we found at Herald Island, Wrangle Island, and on the coast of Asia near Cape North to be about ten fathoms. In Bering Sea we made fast to ice grounded in six fathoms, and passed a number of detached pieces ground in eight fathoms.[1]

Osborn thus describes the ice encountered by McClure off the north coast of Alaska:

> Ice of stupendous thickness and in extensive floes, some seven or eight miles in extent, was seen on either hand; the surface of it is not flat, such as we see in Baffins Strait and the adjacent seas, but rugged with the accumulated snow, frost, and thaws of centuries.[2]

Captain McClintock, in passing around the north coast of Alaska, generally found the heavy ice aground in six or eight fathoms of water,

[1] Capt. C. L. Hooper, "Rept. of the Cruise of the U. S. Revenue Steamer 'Thos. Corwin' in the Arctic Ocean, 1881," *48th Cong. Ex. Doc., No. 204*, p. 128, 1884.

[2] McClure, *The Discovery of the Northwest Passage*, edited by Osborn, p. 83, 1857.

leaving a comparatively ice-free tract of water, three to six fathoms deep, between the ice-pack and the coast, through which he laid his course.[1]

All observers agree in ascribing great thickness to the ice of the Arctic ice-pack. The whalers distinguish it from the ordinary sea ice produced by one or two winters' freezing by calling it the "big ice."

Jarvis, in speaking of the ice-pack of the Alaskan coast, states that

> though the pack contains no real icebergs it nevertheless extends six to eight fathoms below the water and occupies from a third to a half the depth of the shallow Arctic Sea.

Lieutenant Chas. H. Stockton, of the U. S. Navy, thus describes the action of this ice when it is driven ashore:

> Sometimes a long line of heavy floe ice from the pack grounds in the shallow water near the shore during northerly winds, pressed from behind by the force and the weight of the entire northern pack. It is gradually forced up, plowing its way through the bottom, at the same time rising gradually along the ascent of the bottom toward the land.[2]

Lieutenant Stockton made a hydrographic survey of the anchorage near Point Barrow in which he

> demonstrated that the contour of the bottom is constantly changed by the plowing and planing done by the heavy ice grounded and driven up by the pressure of the mighty ice-pack, under the influence of northerly winds and gales.[3]

In this connection the observations and opinion of Mr. A. J. Collier who has seen much of the Arctic coast of Alaska is of interest. He states that

> Dr. E. O. Campbell, government school-teacher at Cape Chibukak, St. Lawrence Island, whose residence is nearly one-half mile back of the beach, reports that he has often feared the destruction of the mission buildings from the same cause (driving ashore of the ice-pack). The beach at Cape Chibukuk is marked by a series of regular ridges parallel to the shore, said by Dr. Campbell to have been pushed up by the ice-pack. In view of these considerations the barrier beaches of the shores of the Arctic Ocean and Bering Sea, though in nearly all respects they resemble the barrier beaches formed by wave and current action in southern altitudes, must in the opinion of the writer be regarded as in part due to material pushed up from the sea-floor by the ice-pack and only transported in a minor

[1] Osborn, *The Discovery of the Northwest Passage*, p. 71, 1857.

[2] Chas. H. Stockton, *Natl. Geog. Mag.*, Vol. II, 1891, pp. 182, 183.

[3] *Ibid.*, p. 182.

degree by wave action. Barrier beaches of this type are of common occurrence along the shores of the Arctic Ocean in Alaska from Cape Prince of Wales to McKenzie River.[1]

The preceding quotations seem to make plain the fact that the pack ice along the Arctic coast should be considered along with currents and waves as one of the most effective agencies concerned in the formation of shore-line features. When it is remembered that the navigable portion of the Arctic Sea northwest of Alaska shoals regularly from a maximum depth of about thirty fathoms toward nearly every part of the Alaskan coast, it will be seen that the conditions are peculiarly favorable for the grounded ice-pack to carry great quantities of submarine deposits to and toward the beaches. The reworking of these transported materials by wave action seldom leaves any permanent features which can be ascribed solely to ice action.

The Arctic ice-pack never retreats far to the north of Point Hope even in midsummer. The observations of Captain A. J. Henderson of the revenue cutter "Thetis" would indicate that it was probably not more than 100 miles to the north of Point Hope at any time during the past summer.

According to Dr. Driggs, the missionary at Point Hope, the ice-pack comes down from the north and closes on the spit before any very considerable amount of local ice has formed on the sea. This usually occurs late in October or in November. In 1908 the bulk of the ice-pack left the Point July 28. It usually leaves early in July. The period during which the Point is subject to wave and current action is therefore limited to about one-fourth of the year. It is probable, however, that the ice-pack is more effective during the other three-fourths of the year in moving submarine materials toward the spit than waves and currents would be.

Mr. Allen, a whaleman who has lived for several years on the Point Hope spit, told the writer that at times in the winter the ice-pack is forced against the south shore of the spit with a force that makes the entire spit tremble as from an earthquake. Joseph Tuckfield, another whaleman who formerly lived on the spit opposite the mouth of the Kukpuk River, was compelled to remove his house to an island in the

[1] A. J. Collier, "Geology and Coal Resources of the Cape Lisburne Region, Alaska," *U. S. G. S. Bull. No. 278*, p. 34, 1906.

inlet on account of the danger of the ice-pack over-riding the spit in winter.

It will readily be seen that a solid ice-pack six or eight fathoms in thickness, which would be of sufficient thickness to ground a little distance off the shore of the Point Hope spit, would be a most effective agent in ridging or piling up in front of it and shoving shorewards the unconsolidated gravels and sand at the bottom, under the influence of pressure from the south. Such a grounded ice-pack driven by the combined pressure of heavy south winds and the north-setting current as the pack starts north in summer undoubtedly plays an important rôle in the growth of the spit by shoving the sands and gravels of the bottom up within the limits of effective wave action. The pack no doubt acts similarly at times in bringing materials up on the northwest shore, but it has already been pointed out that at present destructive agencies are more effective on that side of the spit than are the combined constructive agencies.

Editorial

With this number the *Journal of Geology* begins the publication of the Correlation Papers which were presented to Section E of the American Association for the Advancement of Science in Baltimore, in December, 1908. The first articles are those by President Van Hise and Professor Adams, and deal with the principles of pre-Cambrian geology. Later papers will deal with successive periods or groups of periods, and will appear in chronological order in successive numbers of the *Journal*, as follows: C. D. Walcott: "Evolution of Early Paleozoic Faunas in Relation to Their Environment;" A. W. Grabau: "Physical and Faunal Evolution of North America in the Late Ordovician, Silurian, and Devonian Time;" Stuart Weller: Correlation of Middle and Upper Devonian and Mississippian Faunas of North America;" G. H. Girty: "Physical and Faunal Changes of Pennsylvanian and Permian in North America;" David White: "The Upper Paleozoic Floras, Their Succession and Range;" S. W. Williston: "Environmental Relations of the Early Vertebrates;" T. W. Stanton: "Succession and Distribution of Later Mesozoic Invertebrate Faunas;" W. H. Dall: "Conditions Governing the Evolution and Distribution of Tertiary Faunas;" Ralph Arnold: "Environment of the Tertiary Faunas of the Pacific Coast;" F. H. Knowlton: "Succession and Range of Mesozoic and Tertiary Floras;" H. F. Osborn: "Environment and Relations of the Tertiary Mammalia;" Rollin D. Salisbury: "Physical Geography of the Pleistocene with Special Reference to Conditions Bearing on Correlation;" D. T. MacDougal: "Relation of Plants to Climate with Special Reference to Pleistocene Conditions;" T. C. Chamberlin: "Diastrophism as the Ultimate Basis of Correlation."

With these papers, several of Mr. Willis' maps of the North American continent, at various stages of its history, will be published, together with some explanatory notes. It is hoped that these articles will prove to be of general interest to readers of the *Journal*, as they were to those who heard them in Baltimore. It is possible that the several articles will be issued in book form, after the series is completed.

R. D. S.

Reviews

Stratigraphy and Paleontology of the Ordovician Rocks of Indiana. By E. R. Cumings. Thirty-second Annual Report of the Department of Geology and National Resources of Indiana, 1907, pp. 607–1188.

Professor Cumings has determined as accurately as possible the exact range and horizons of the different fossil species found by him in the Ordovician strata of southern Indiana and finds that the strata fall naturally into eight zones differentiated faunally as well as lithologically. Nickles in his earlier work used the bryozoa in determining the several divisions he proposed for these strata but Cumings, believing that the brachiopods are more generally suited especially for field determination, has used the latter as indicators. An important result of the present work is the discovery that in the Richmond beds the Saluda beds lie below, rather than above the Whitewater beds as believed by Foerste and others. The general absence of the later beds to the south is believed to indicate an extensive unconformity between the Richmond and the overlying Clinton. The major part of the paper is taken up with redescriptions of the fossils mainly drawn from the original descriptions.

The careful stratigraphic work is a credit to Professor Cumings and an advance in the right direction.

J C. J.

The Geology of the Gold Fields of British Guiana. By J. B. Harrison, Director of the Department of Science and Agriculture and Government Geologist. With Historical, Geographical, and other chapters by Frank Fowler and C. Wilgress Anderson.

Since 1884, when gold mining on an important scale was first undertaken, British Guiana has produced about $35,000,000 gold, most of which has been recovered from placer and residual deposits. The gold-bearing area is said to cover more than 1,000 square miles. The country is heavily forested and the rocks are exposed mainly along the streams and in ravines where torrential rains have cut through the deep residuum.

The oldest rocks are crystalline schists, probably of pre-Cambrian age, which vary in character from granitic gneiss to very basic schist. This

series is intruded by a great variety of porphyritic rocks and is overlaid by sandstones and conglomerates forming a series from 2,000 to 3,000 feet thick, which is in the main flat lying and is not greatly deformed. This group of rocks is not known to contain fossils, but its relationship to rocks of known age is said to have been made out in Venezuela where it is regarded as Cretaceous. The schists and the sandstones are intruded by diabase which the author regards as a source of much of the gold. The relatively fresh rock carries from a trace to 17 grains per ton.

Owing to the humid climate and tropical vegetation the rocks have weathered to great depth. Laterite, the residual product of the basic rocks, is known to be as much as 100 feet deep in some places. In the laterite there is a marked concentration of iron and clay and locally of gold, which it carries in amounts varying from traces to 15 pennyweights per ton. The laterite also contains irregular masses of rich quartzose ore which is presumably altered vein-stuff, but such masses are not abundant and the conclusion is that not more than 10 per cent. of the placers have originated from quartzose ores. The principal source is regarded as the basic igneous rocks in which, through decomposition to laterite, there has been a marked concentration *in situ*. Further concentration has taken place in some of the stream gravels. From the descriptions given, the laterite areas seem to offer attractive fields for prospecting for large low-grade gold deposits which should be very economically worked.

W. H. E.

The World's Gold. By L. De Launay, with an Introduction by C. A. Conant. Translated by Orlando Cyprian Williams. New York and London: G. P. Putnam's Sons.

This work is arranged for the banker and economist, rather than the geologist and metallurgist. The geographic distribution and the extraction of gold are treated in an interesting and readable manner, but the future production of gold is obviously the subject which is of greatest importance. Statistics are given which show that the gold production of the world has steadily increased since the Boer war, reaching over four hundred million dollars in 1906. The writer concludes that the next fifteen years will probably be marked by a great production of gold, which will afterward decline. He concludes, however, that the supply will be adequate for the purposes required, owing to a more general use of instruments of credit.

W. H. E.